Jet Physics with ALICE at the LHC

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28th High Energy Nuclear Physics Seminar in China, July 17th 2014

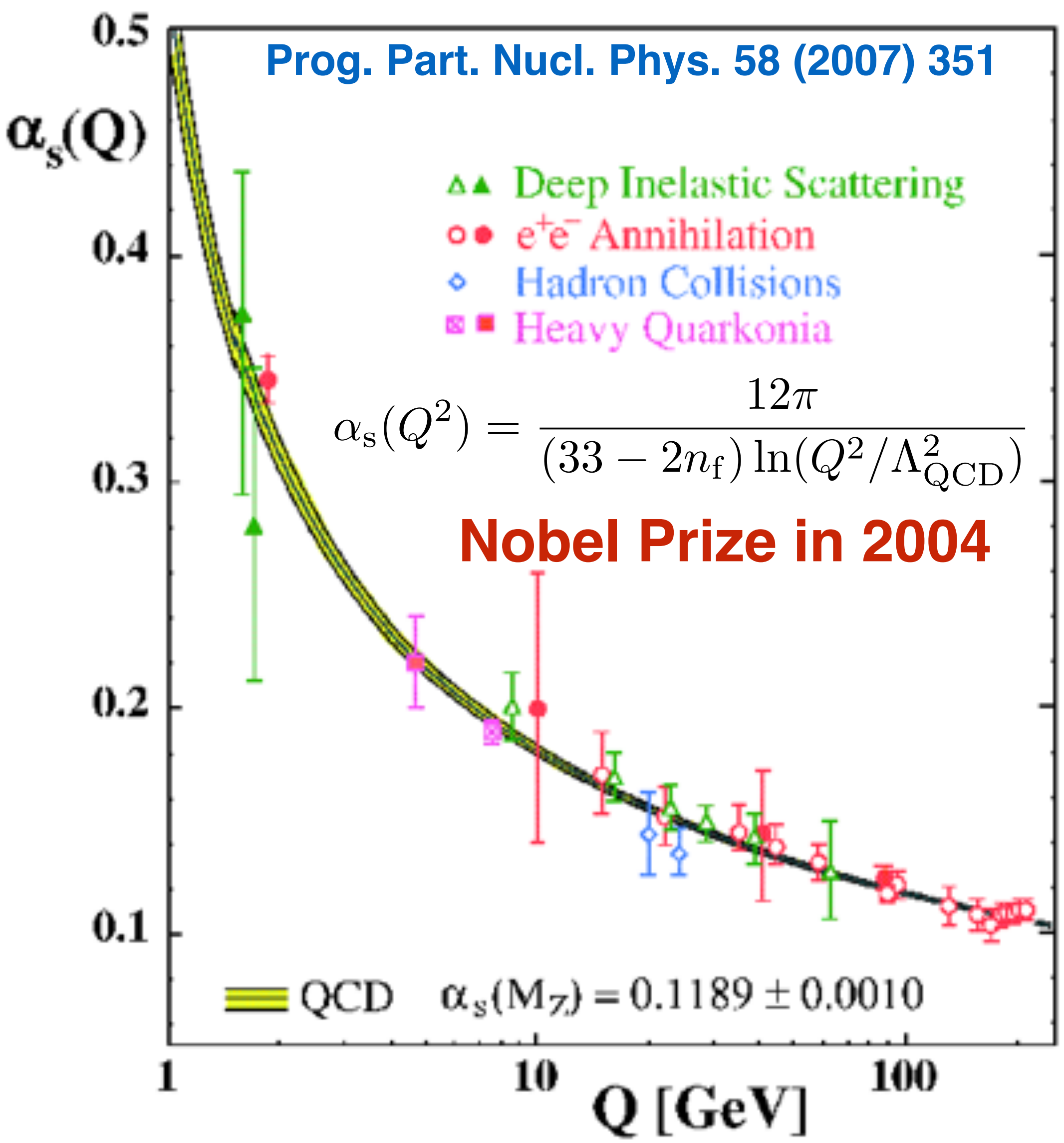
Outline

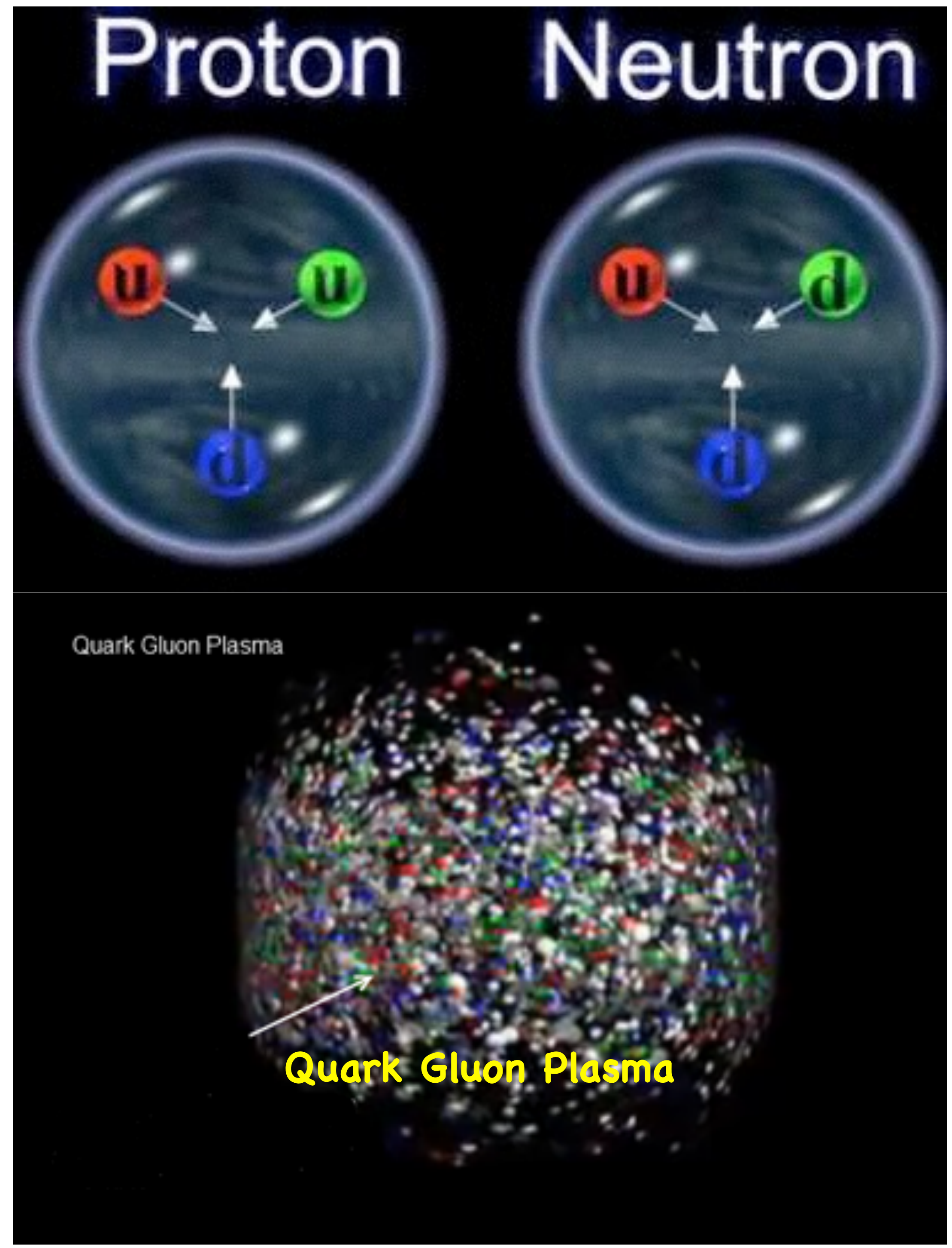
- Introduction
- Experimental Aspects of Jet Reconstruction
- Jets in ALICE
- Summary and Outlook

Jet Physics

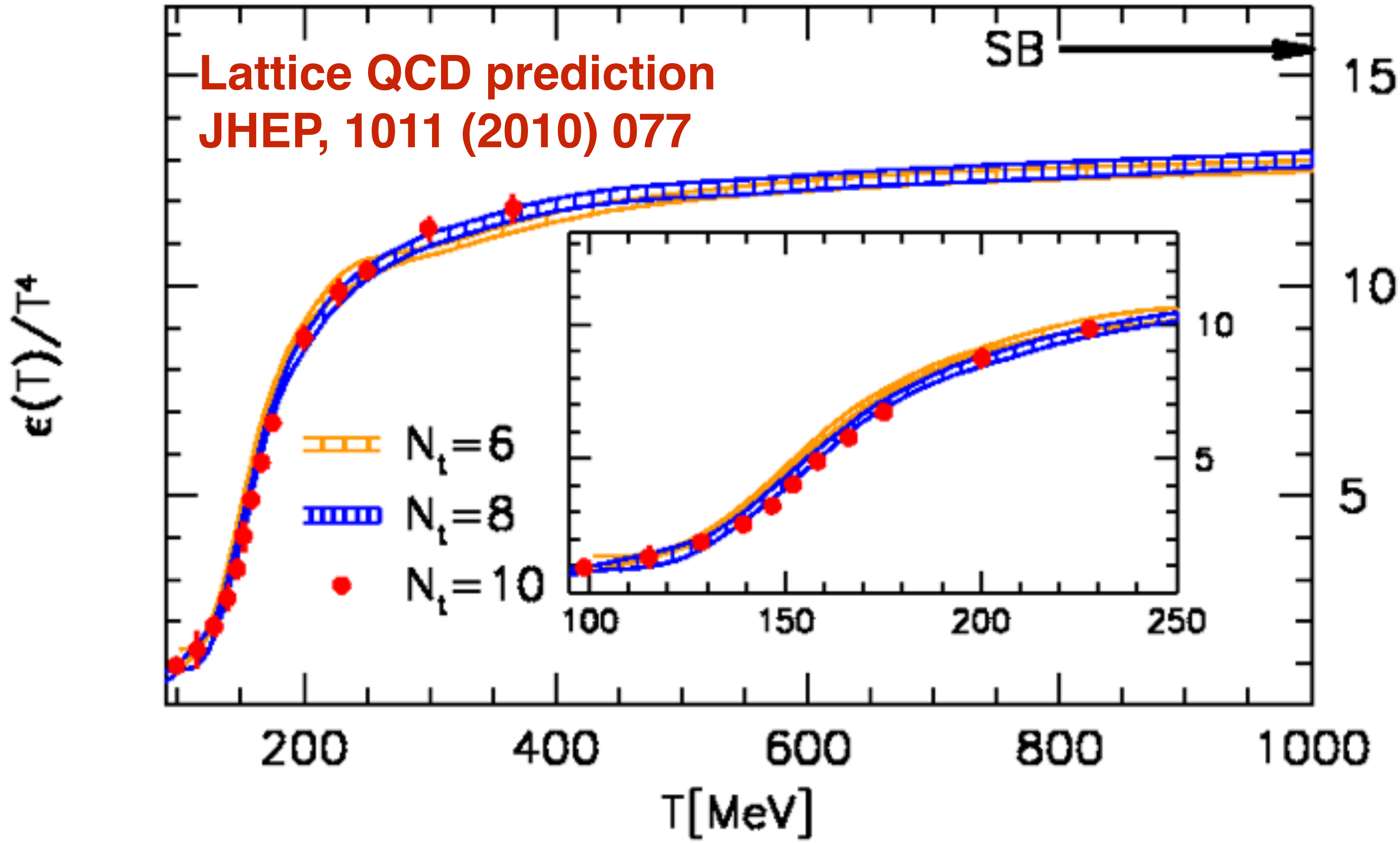
QCD Phase Transition

$$\mathcal{L} = \sum_q \overline{\psi}_{q,a}(i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t^C_{ab} \mathcal{A}^C_\mu - m_a \delta_{ab})\psi_{q,b} - \frac{1}{4} F^A_{\mu\nu} F^{A,\mu\nu}$$



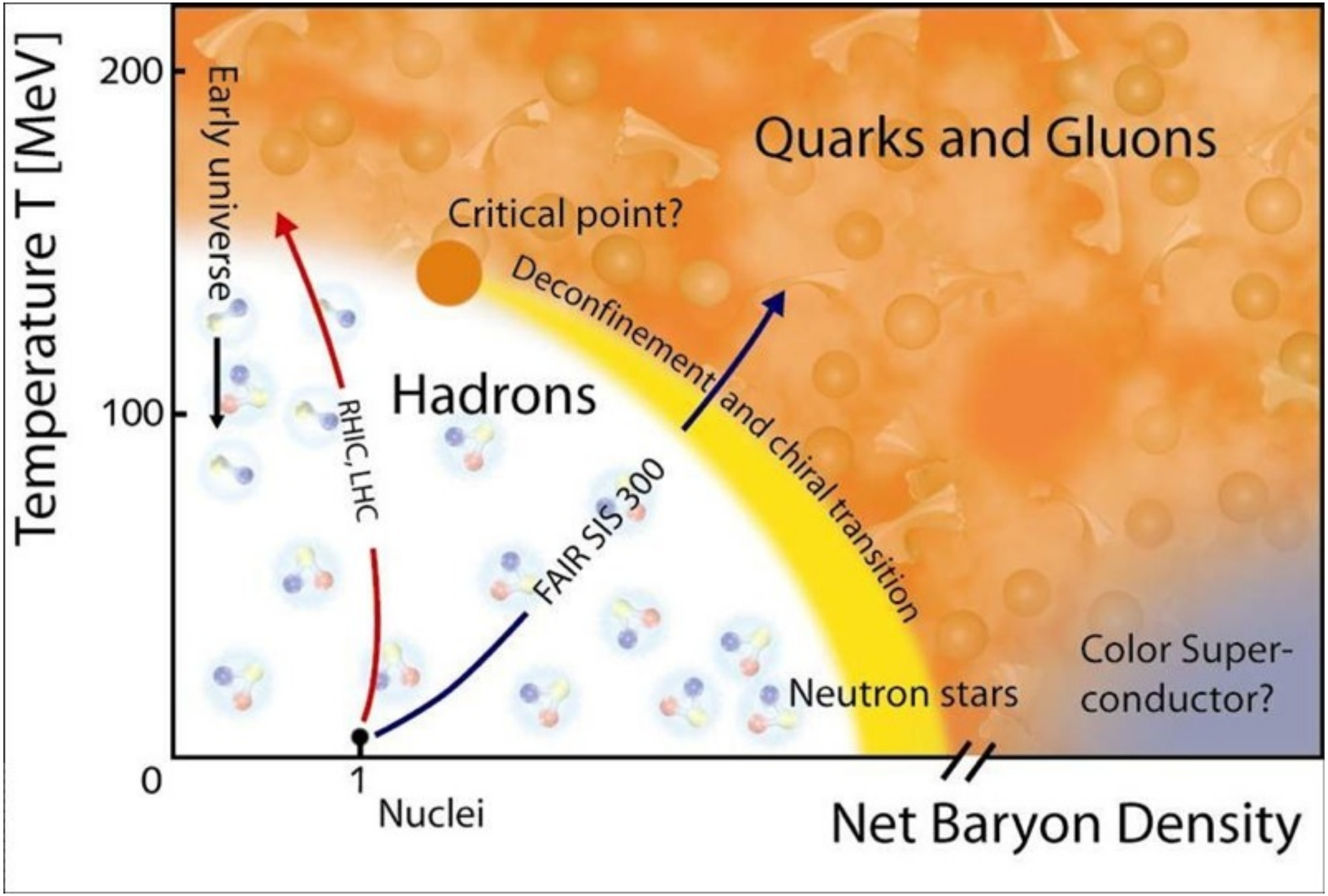


QCD Phase Transition

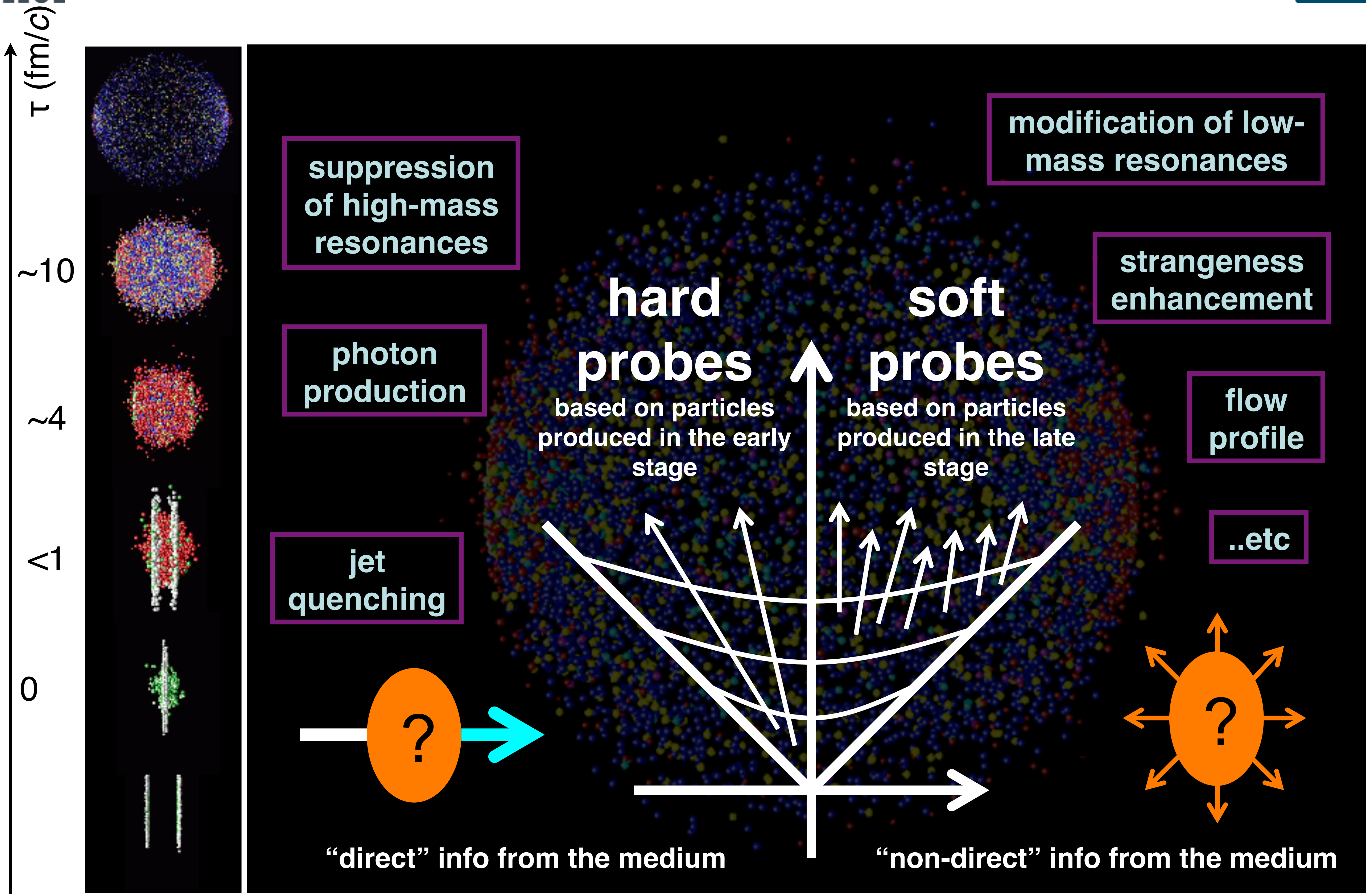


- Sharp increase of energy density around $T_c = 170$ MeV indicates a phase transition from hadronic matter to deconfined Quark Gluon Plasma (QGP)

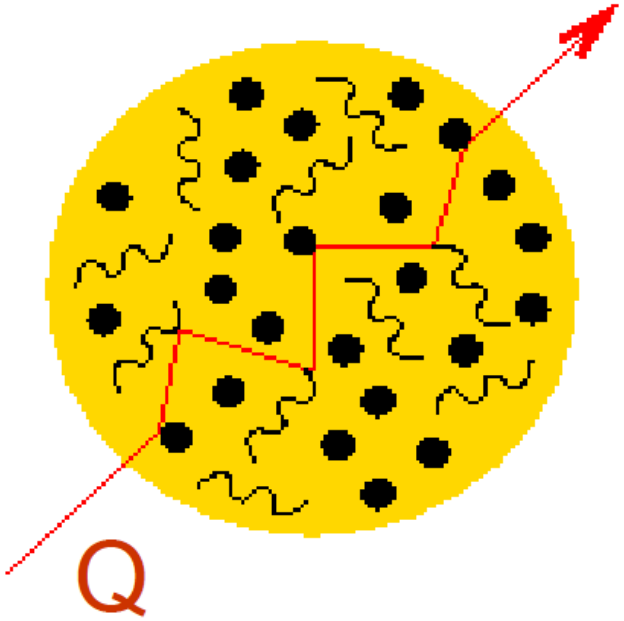
QCD Phase Diagram



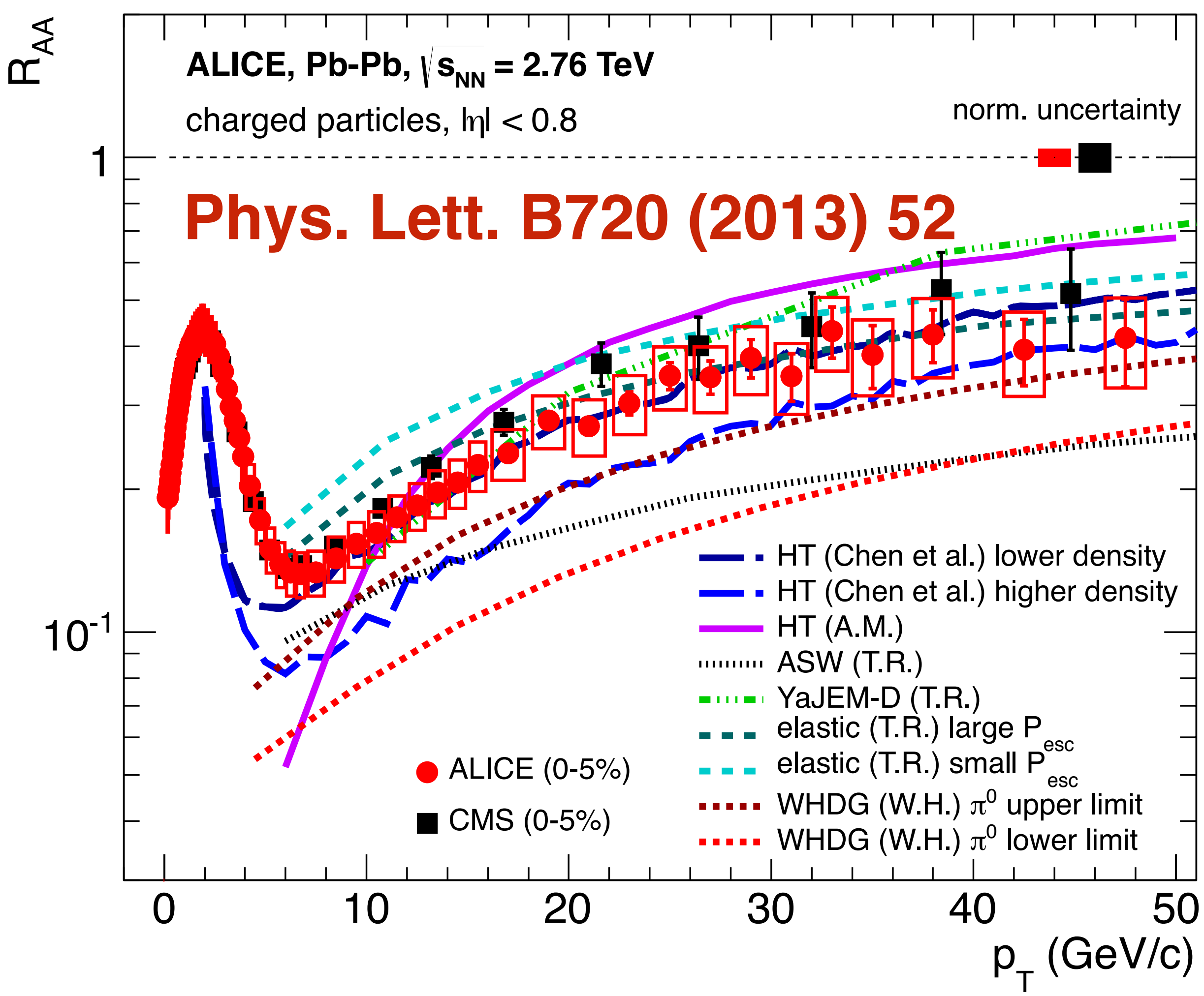
Heavy-Ion Collisions



Jet Quenching

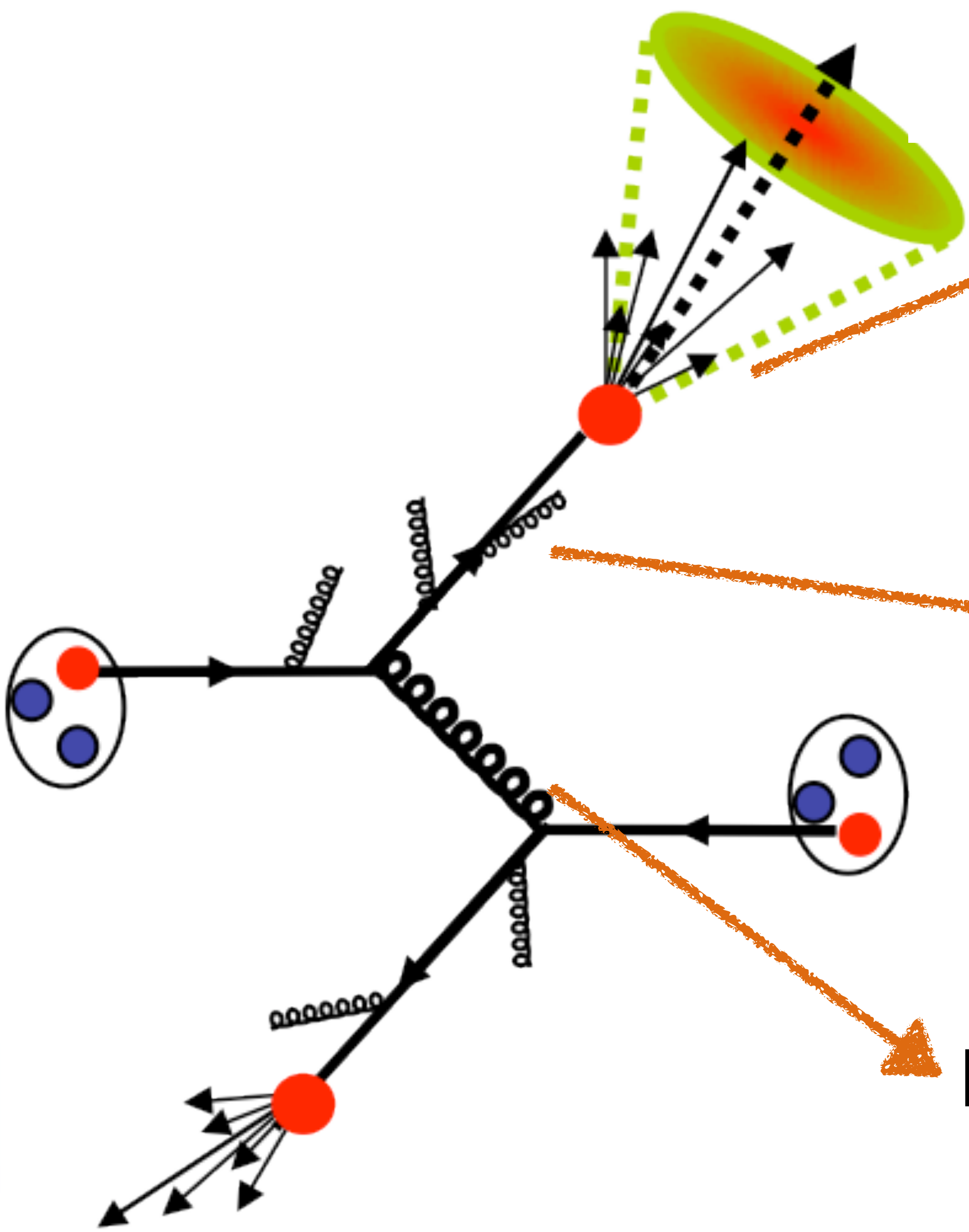


- Jet quenching: parton in-medium energy loss
  - observed charged hadron suppression in heavy-ion collisions



- Time to quantify the jet quenching mechanisms via the reconstructed jets
  - ✓ avoid surface bias
  - ✓ better connection to theory
  - ✓ assessing jet quenching at partonic level

Jets in Proton–Proton Collisions



Hadronization into a colorless spray of particles — **Jet**

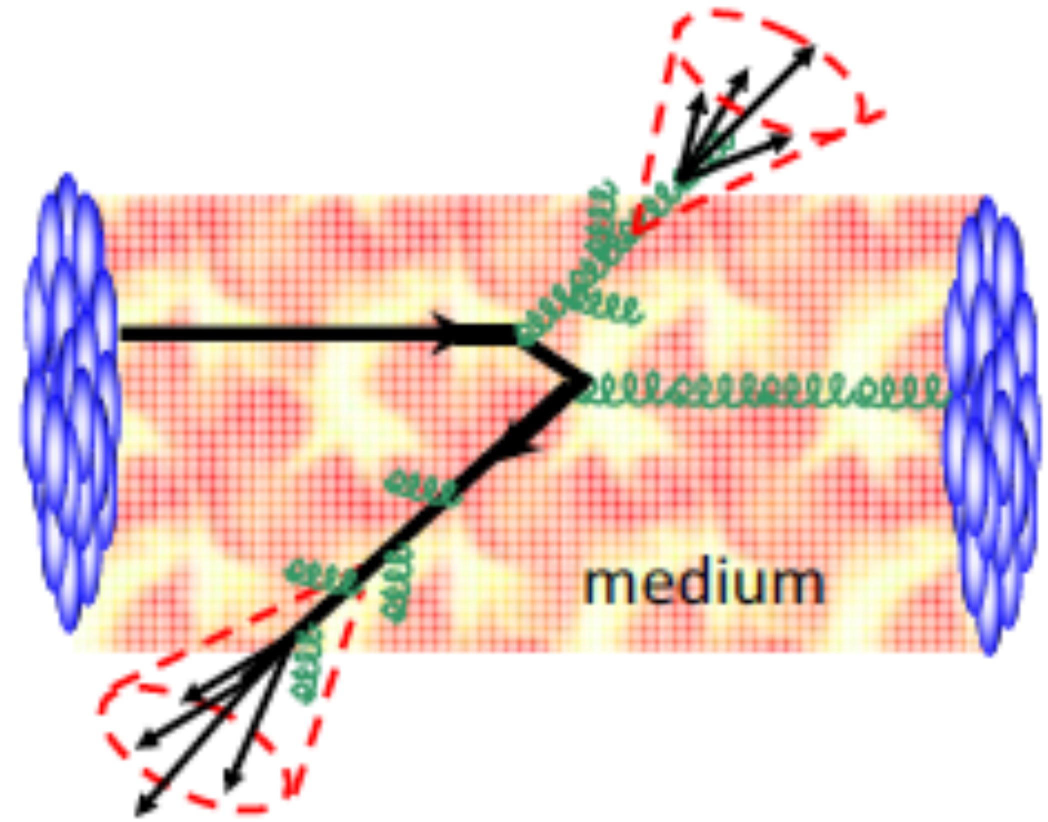
Radiation of (soft) gluons and quarks

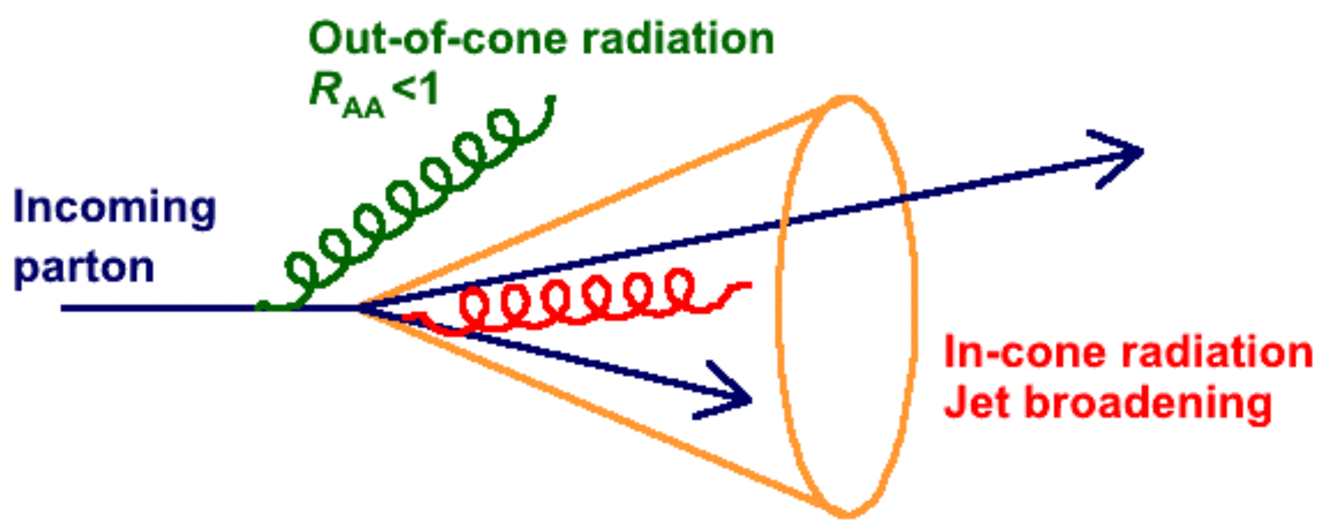
Initial parton hard scattering ($Q^2 >> \Lambda_{QCD}$)

Jets are attractive both experimentally and theoretically

Jets in Heavy-Ion Collisions

- Hard protons produced before the QCD medium forms
- Interact with the hot dense medium



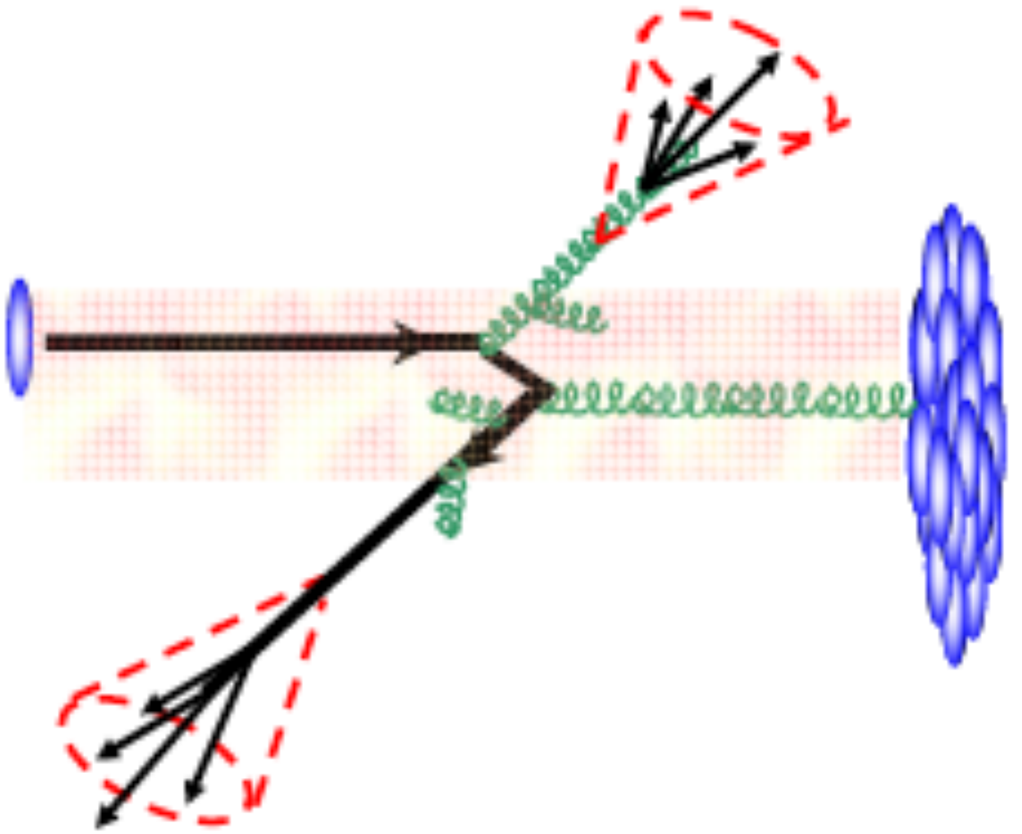


$$R_{\mathrm{AA}} = \frac{1/T_{\mathrm{AA}} 1/N_{\mathrm{ev}} \mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

- Out-of-cone radiation: energy loss in jet cone
  ➡jet yield suppression, dijet or hadron jet acoplanarity…
- In-cone radiation: medium modified fragmentation function
  ➡jet shape bordering, modification of transverse energy profile…

Jets in Proton–Nuclear Collisions

- Study of cold nuclear matter
  - initial state effects:
    ➡ Color Glass Condensate (CGC)?
    ➡ nuclear modified Paton Distribution Function (nPDF)…



  - final state effects:
    ➡ parton scattering in cold nuclear matter…

- baseline for the heavy-ion collisions:
  ➡ disentangle the initial state effects from the hot and dense medium produced in the final state of the heavy-ion collisions

Jet Reconstruction in an Experiment

Jet Finder

- Experiment does not know about initial partons and the evolution just about the final detected particles
- Jet finder algorithm: assemble particles to obtain the physical observable
  - infrared and collinear safe: soft emission and collinear splitting should NOT change jets
  - identical defined at parton and hadron level: calculations can be compared to experiments
- Two main jet algorithm classes
  - cone-type algorithms: identify energy flow in cones — infrared and collinear safe must be carefully studied
  - sequential clustering algorithms: pair-wise successive recombinations — simple definition, infrared and collinear safe

Sequential Clustering Algorithms

1. For each pair of particles, i and j, calculate:

$$d_{ij} = \min\{p_{\mathrm{T},i}^{2n}, p_{\mathrm{T},j}^{2n}\}\frac{(\eta_i - \eta_j)^2 + (\varphi_i - \varphi_j)^2}{R}, \begin{cases} n = 1 & k_{\mathrm{T}} \text{ algorithm} \\ n = 0 & \text{C/A algorithm} \\ n = -1 & \text{anti-}k_{\mathrm{T}} \text{ algorithm} \end{cases}$$

   R is resolution parameter which is one of the inputs of the jet finder

2. if $d_{ij} = \min\{d_{ij}, p_{\mathrm{T},i}^{2n}, p_{\mathrm{T},j}^{2n}\}$, merge particles i and j into a single particle:

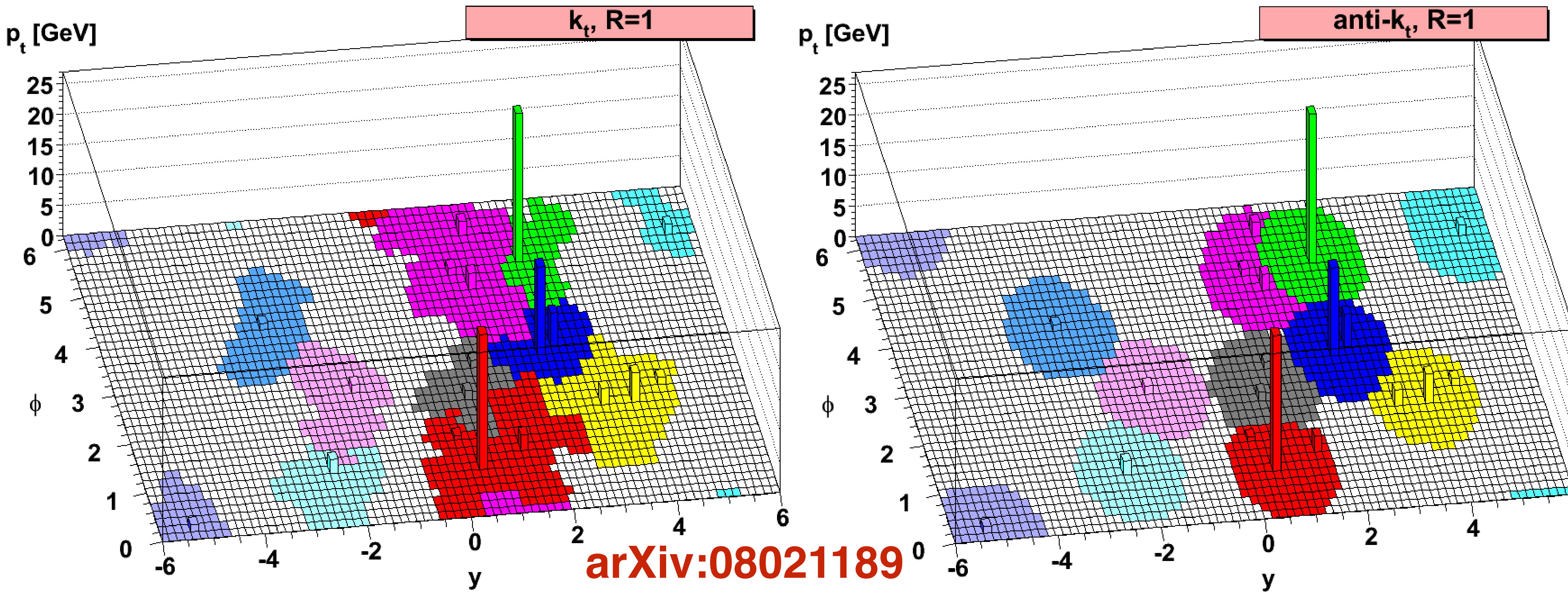
$$\begin{aligned} p_{\mathrm{T},r} &= p_{\mathrm{T},i} + p_{\mathrm{T},j} \\ \varphi_r &= (w_i\varphi_i + w_j\varphi_j)/(w_i + w_j) \\ \eta_r &= (w_i\eta_i + w_j\eta_j)/(w_i + w_j) \end{aligned}$$

   $w_i = 1, p_{\mathrm{T},i}, p_{\mathrm{T},i}^2$ for different recombination schemes

3. repeat from step 1 until no particle is left

Jet Area: k_T vs. anti-k_T

- The jet area can be used to access jet susceptibility to contaminations: underlying background, pileup…



- k_T: the detailed jet shapes are in part determined
- anti-k_T: more like the circles — insensitive to soft radiation

Measured Jets in Experiment

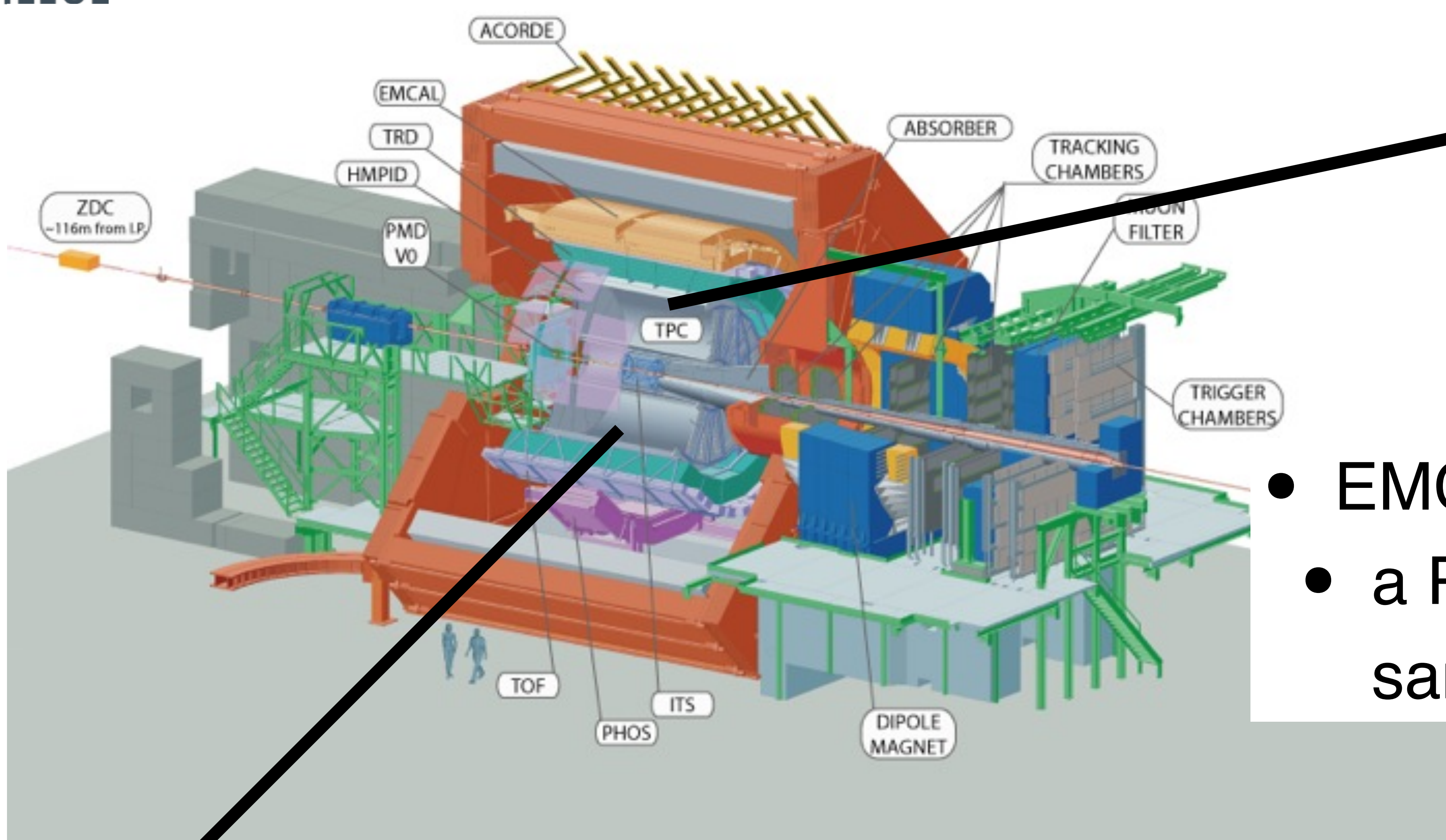
- Reporting a jet with p_{T} = 100 GeV/c in data is meaningless

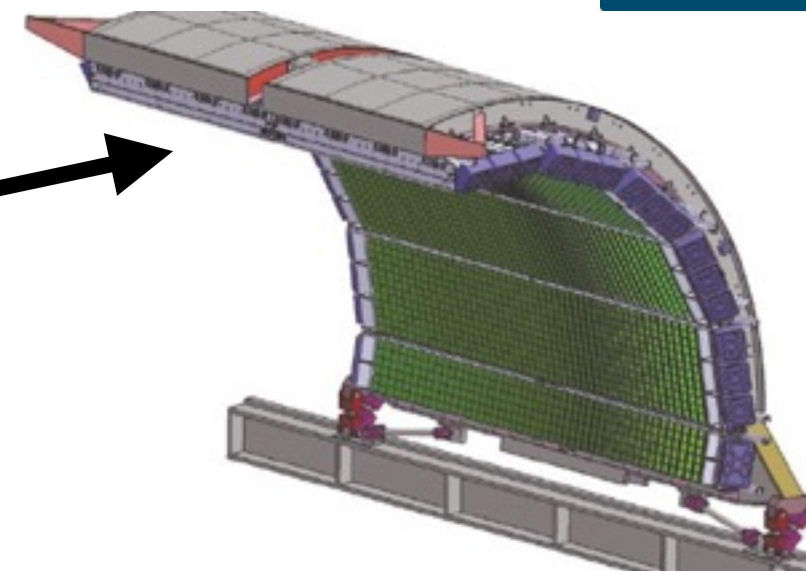
- A correct way the define a measured jet is:
  - a full (or charged) jet at p_{T} = 100 GeV/c
  - with resolution parameter (jet cone size) $R = 0.2$
  - reconstructed by anti-k_{T} algorithm with $p_{\mathrm{T}}/E_{\mathrm{T}}$-scheme

- But one has to keep in mind that the measured jet p_{T} may be contaminated by:
  - energy redistribution, detector effects and underlying background and background fluctuations…

Jet Measurement with ALICE Detector

Jet Measurement with ALICE





- EMCal: |η|<0.7, 1.4<ϕ<π
  - a Pb-scintillator sampling calorimeter

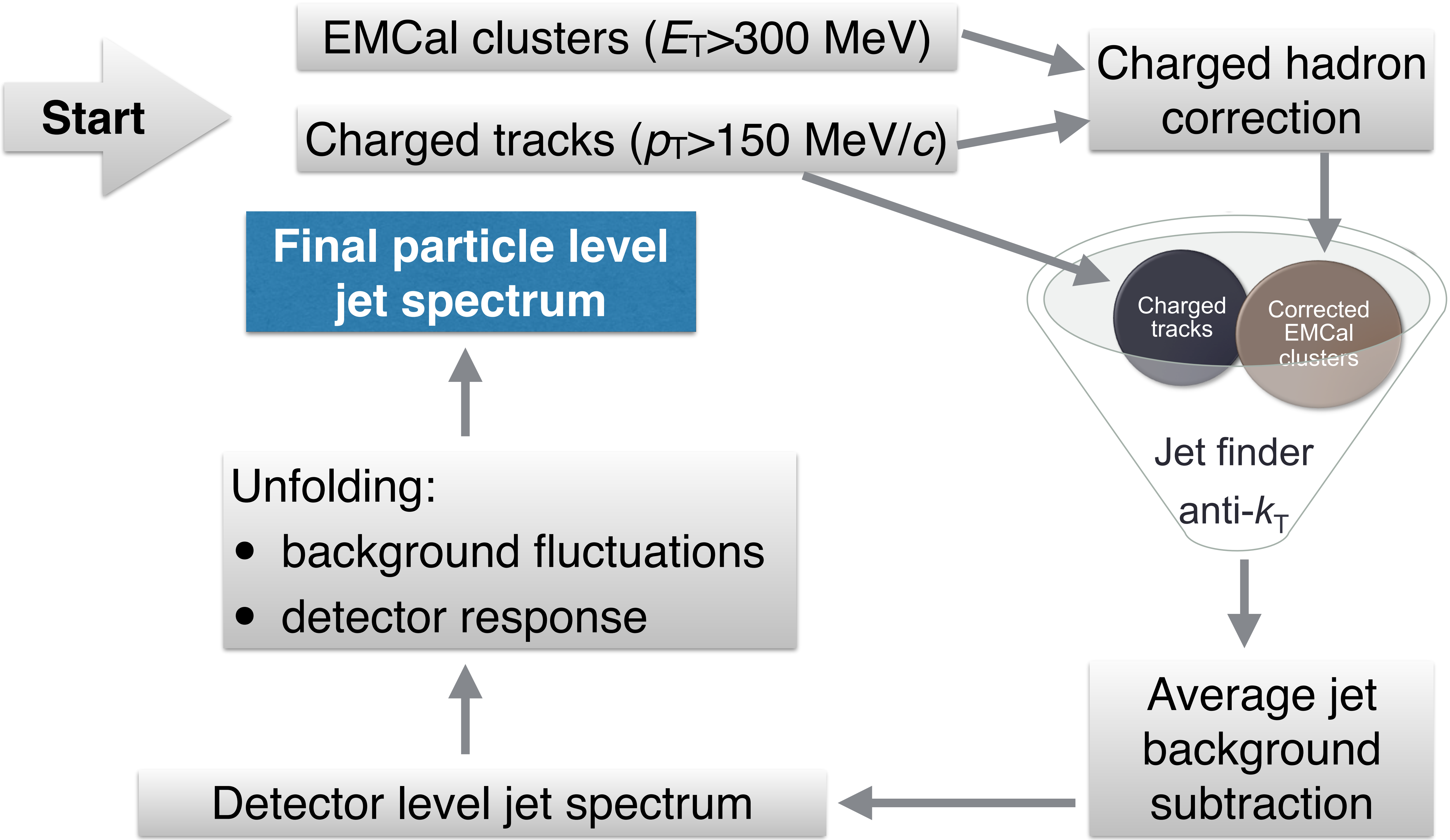
Charged particle correction: prevents energy double counting

- Tracking: |η|<0.9, 0<ϕ<2π
  - TPC: gas draft detector
  - ITS: silicon detector

Charged constituents

Neutral constituents

Analysis Workflow



Average Background Density

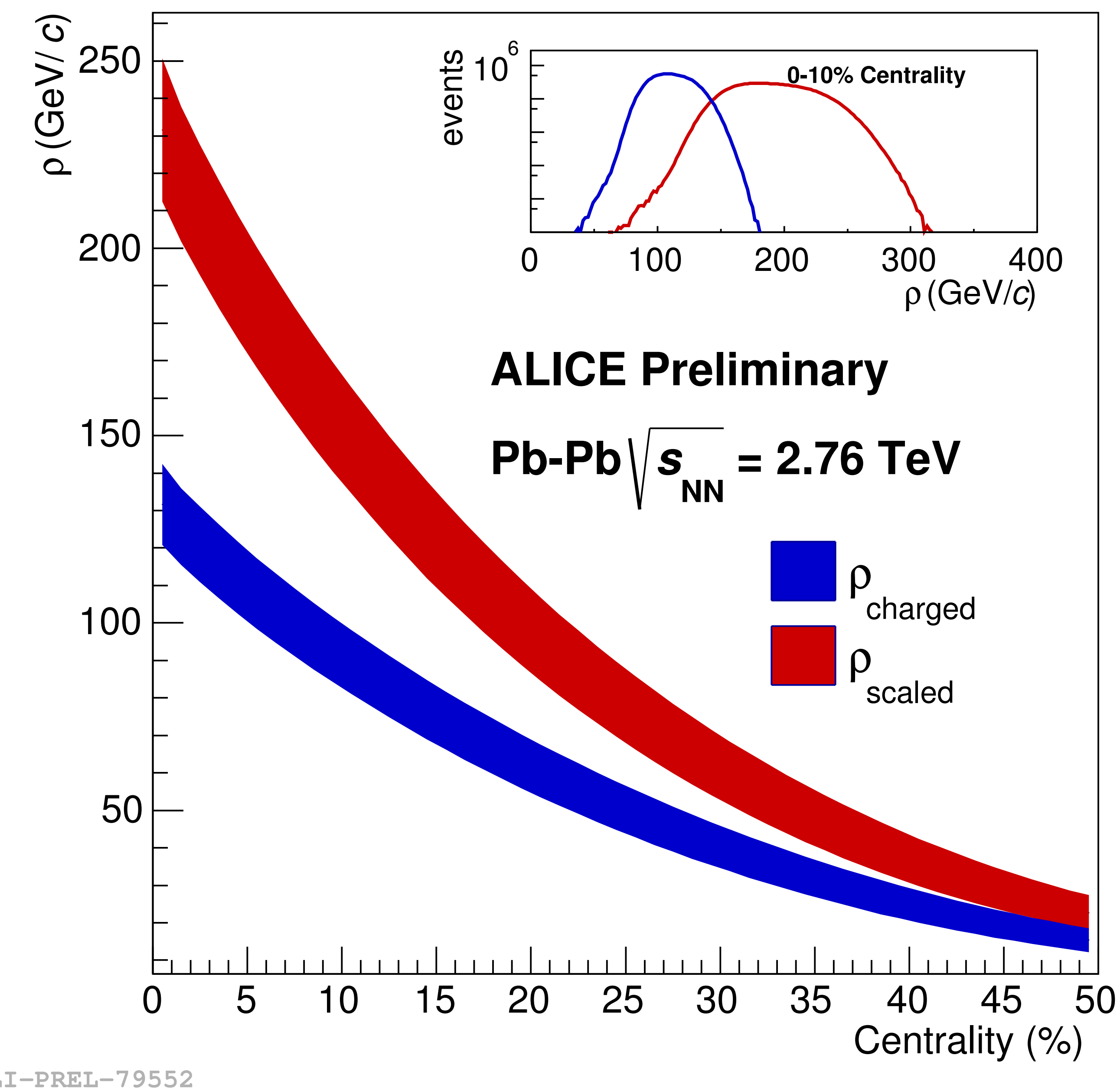
- Event-by-event background is obtained using the charged particle jets reconstructed by k_T algorithm

$$\rho_{\text{charged}} = \text{median}\left(\frac{p_{\mathrm{T},k_\mathrm{T}\text{jet}}^{\text{ch}}}{A_{k_\mathrm{T}\text{jet}}^{\text{ch}}}\right)$$

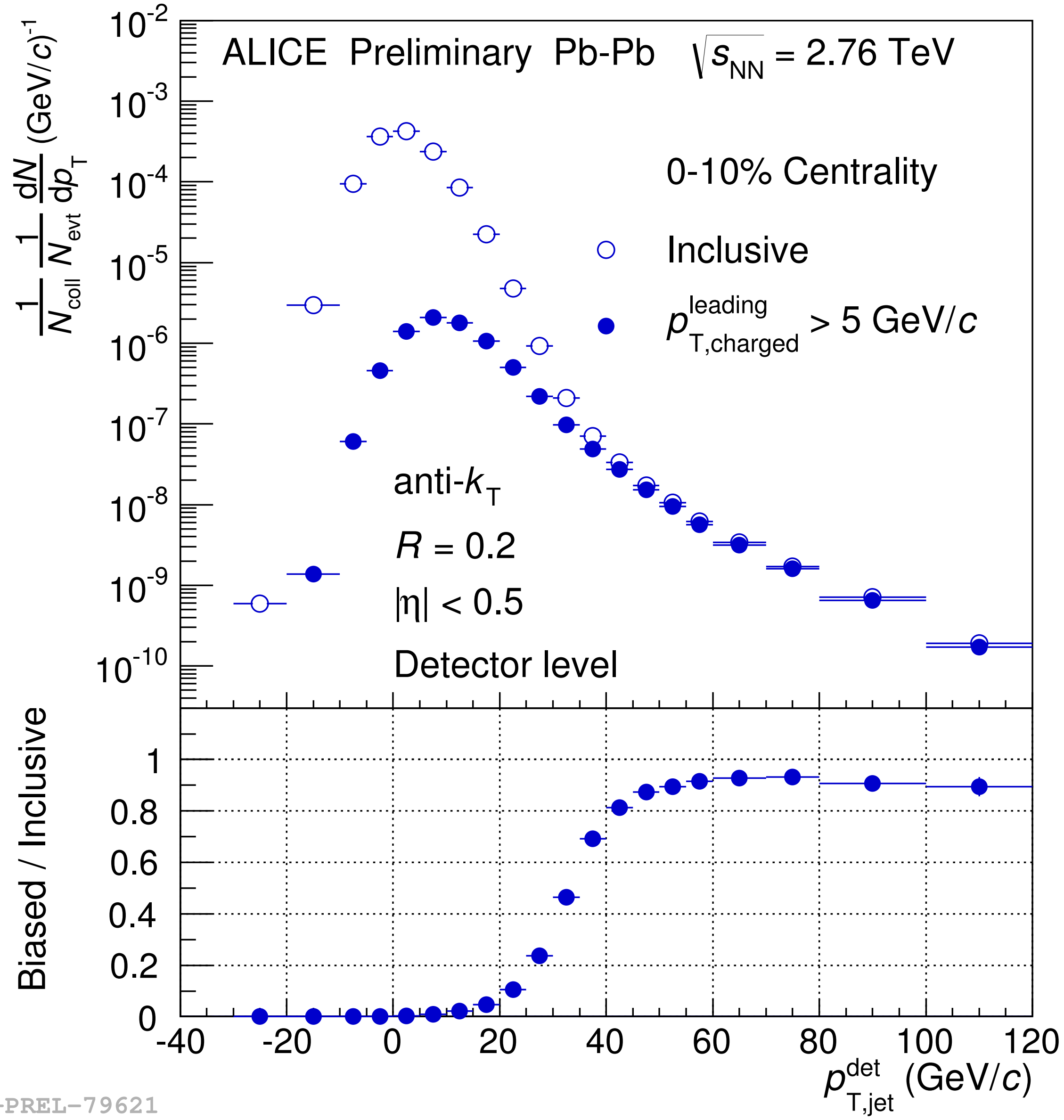
- Scaled to account for neutral energy

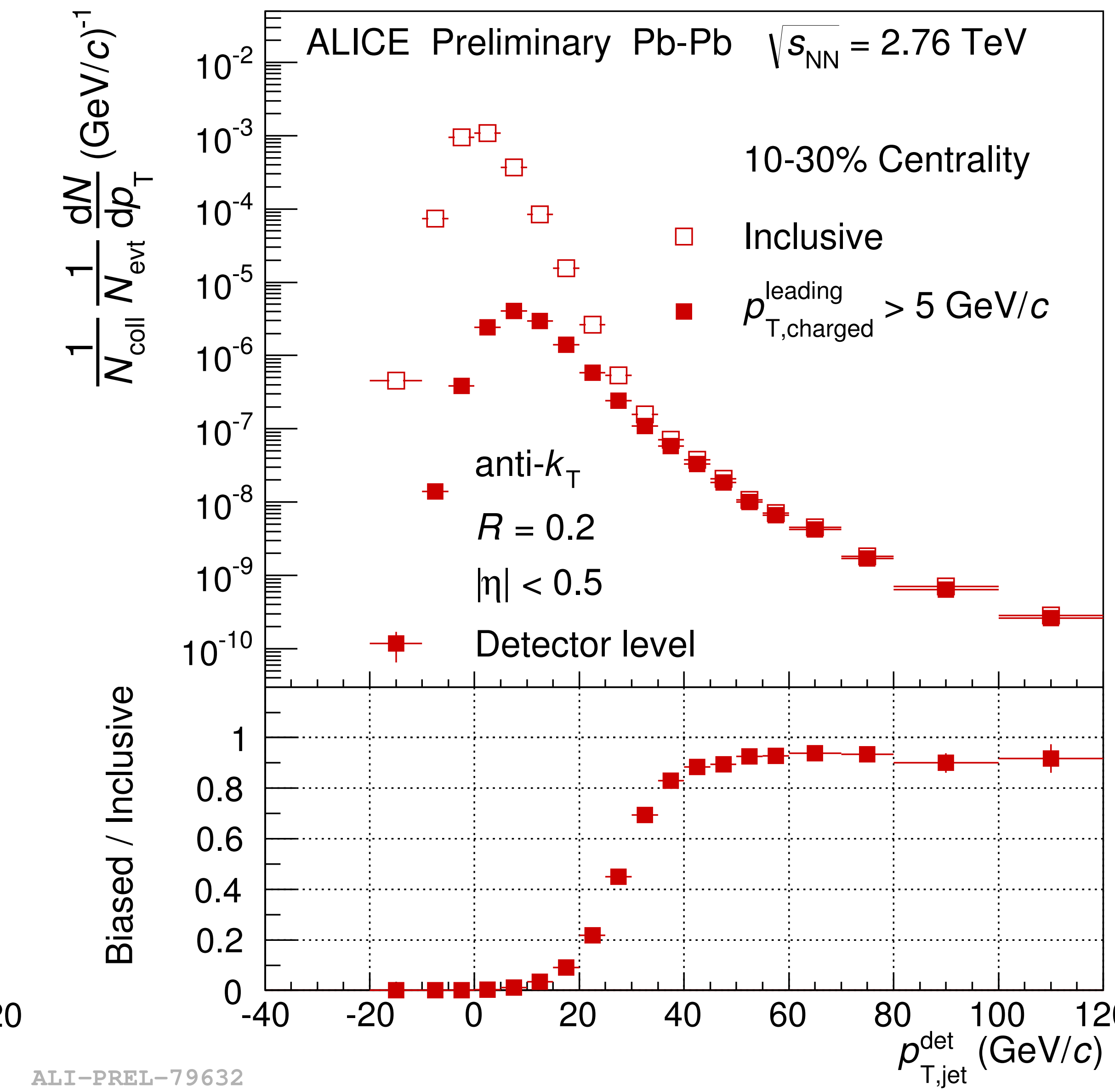
$$\rho_{\text{scaled}} = \rho_{\text{charged}} \frac{\sum E_\mathrm{T}^{\text{cluster}} + \sum p_\mathrm{T}^{\text{track}}}{\sum p_\mathrm{T}^{\text{track}}}$$

- Background density in most central Pb–Pb event:
  - ~200 GeV/*c* per unit area
  - ~25 GeV/*c* for *R*=0.2 jets



Jet Spectra at Detector Level





- With charged leading hadron p_T>5 GeV/c
  - suppress combinatory background
  - bias towards harder fragmentation

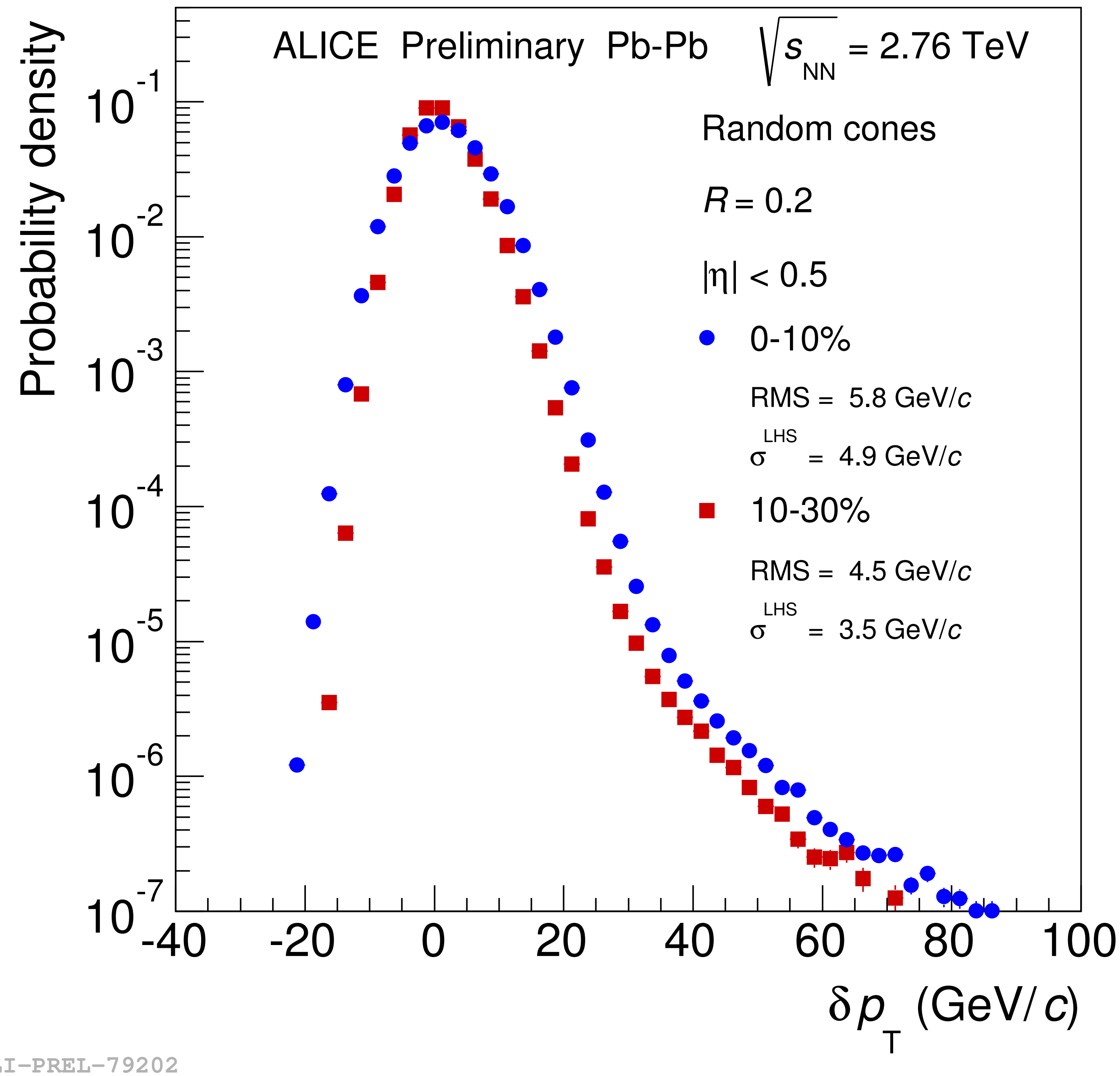
$$\boxed{p_{\mathrm{T,jet}}^{\mathrm{det}} = p_{\mathrm{T,jet}}^{\mathrm{meas}} - \rho A_{\mathrm{jet}}}$$

Background Fluctuations: Random Cone

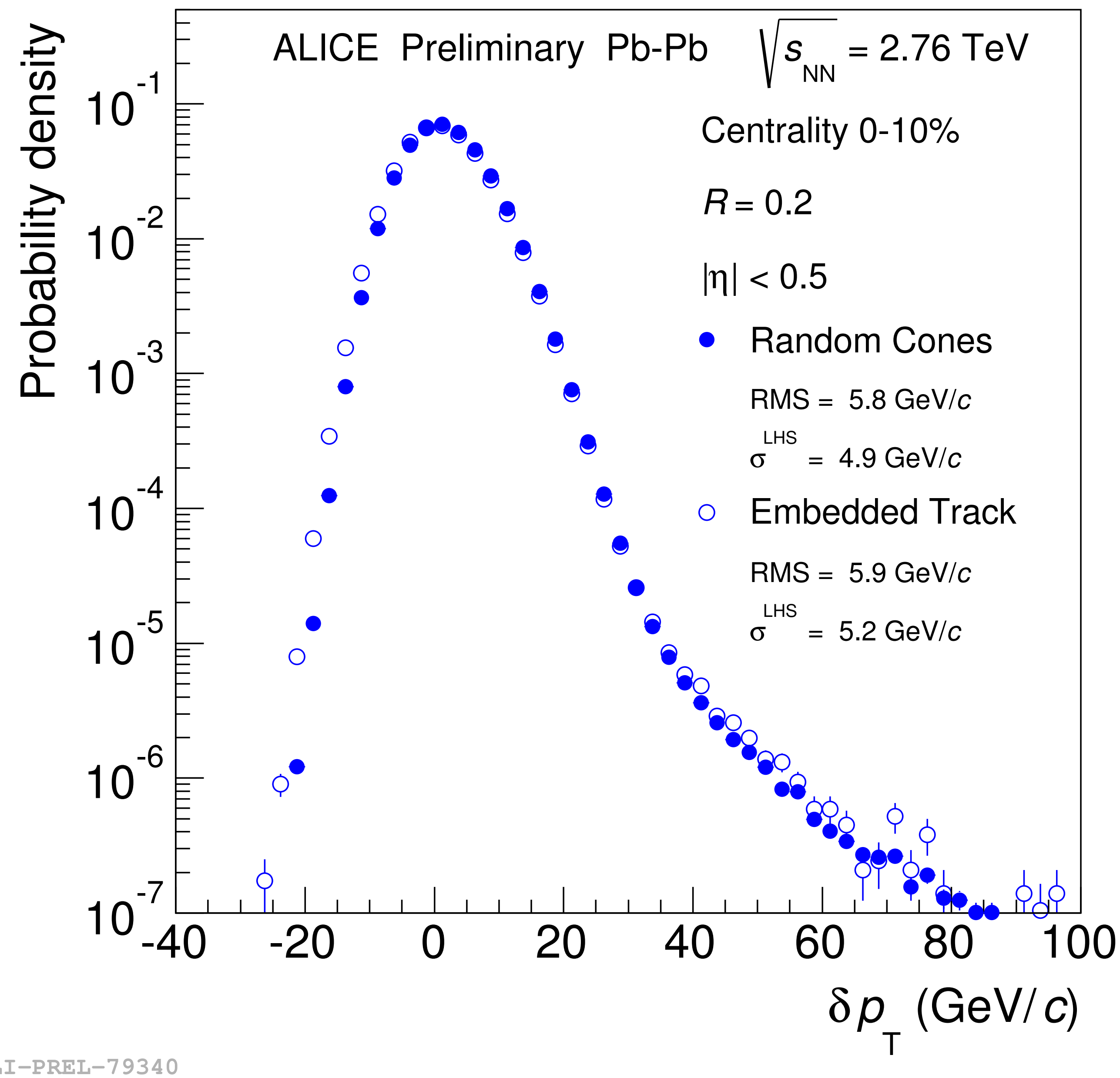
- The size of background fluctuations is characterized by δp_T

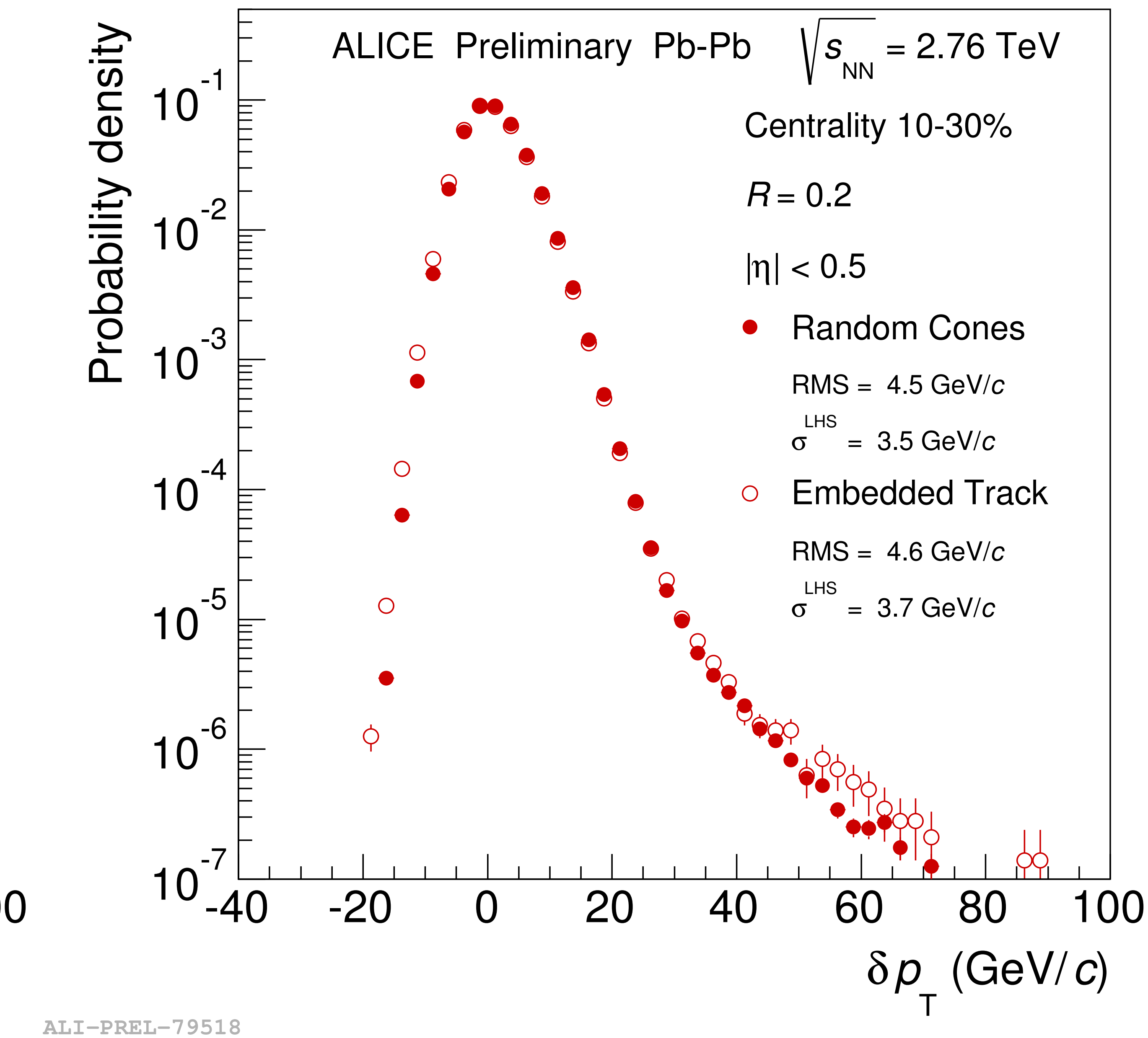
$$\delta p_{\mathrm{T}} = \sum_{\mathrm{RC}} p_{\mathrm{T,part}} - \rho_{\mathrm{scaled}} \times \pi R^2$$

- Asymmetry distribution
  - LHS: Gaussian-like — dominated by soft particle production
  - RHS: tail due to hard particles — jets overlap



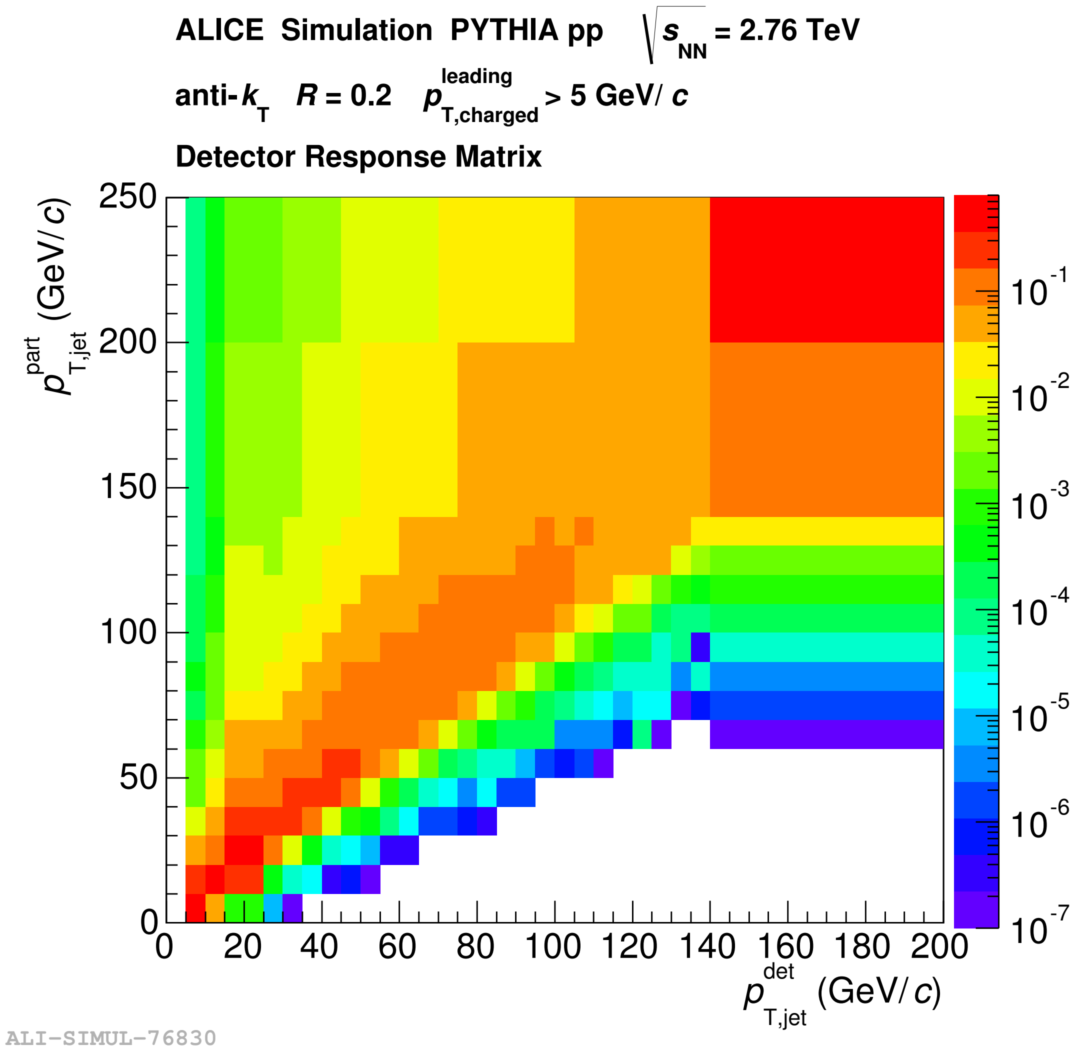
Background Fluctuations: Embedding

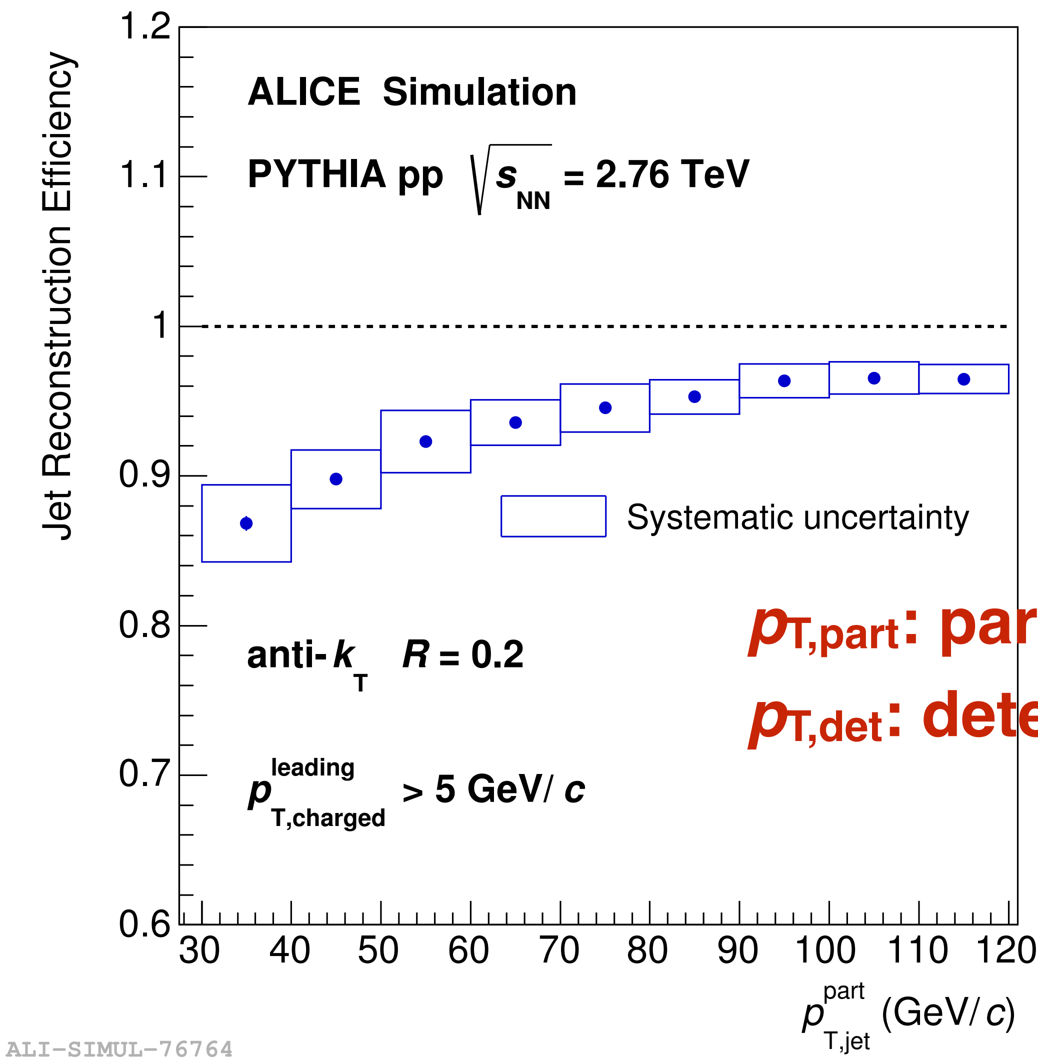




- Single particle embedding δp_T is compared with random cones
  - difference gives the the uncertainty on background fluctuations

Detector Effect





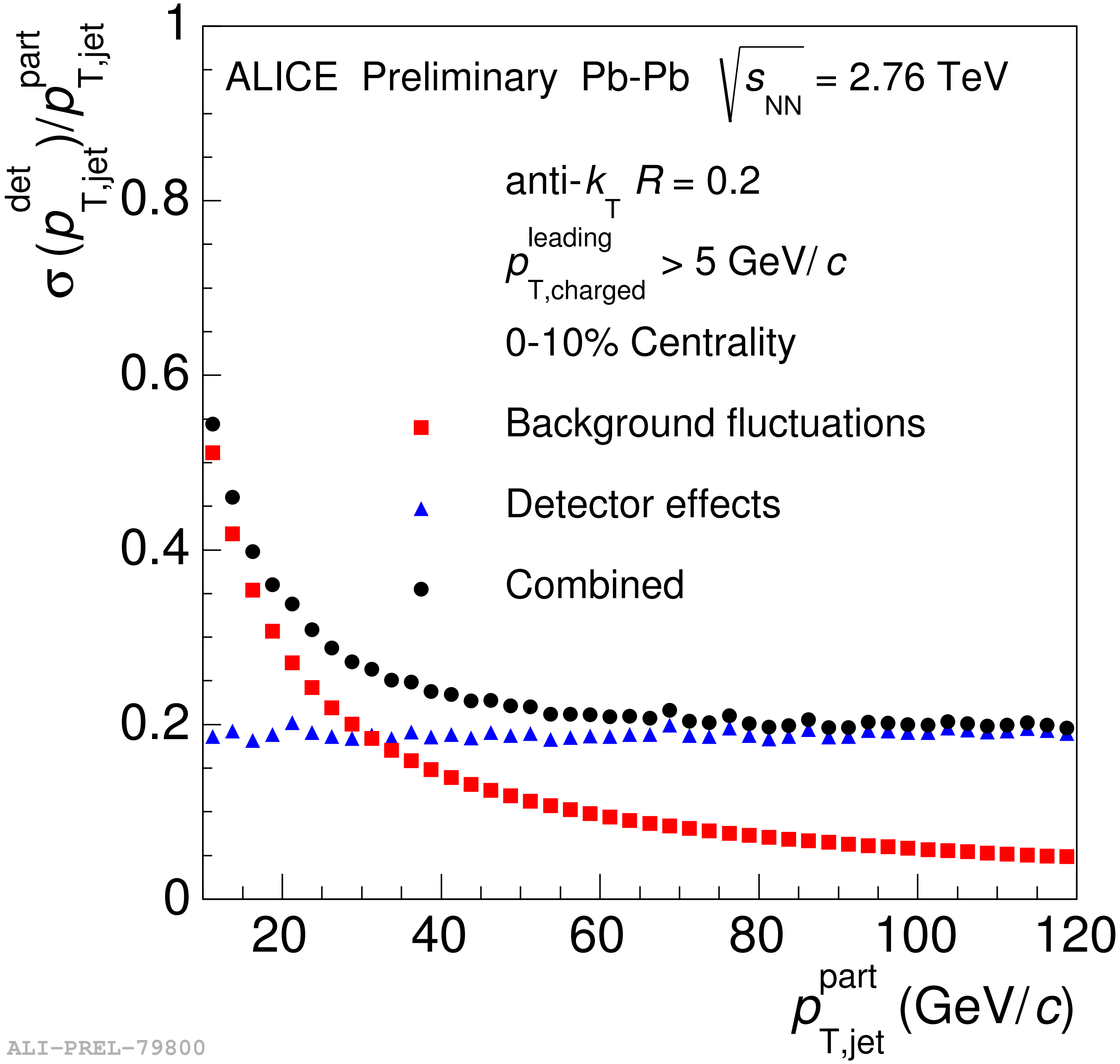
$p_{T,part}$: particle level jet p_T

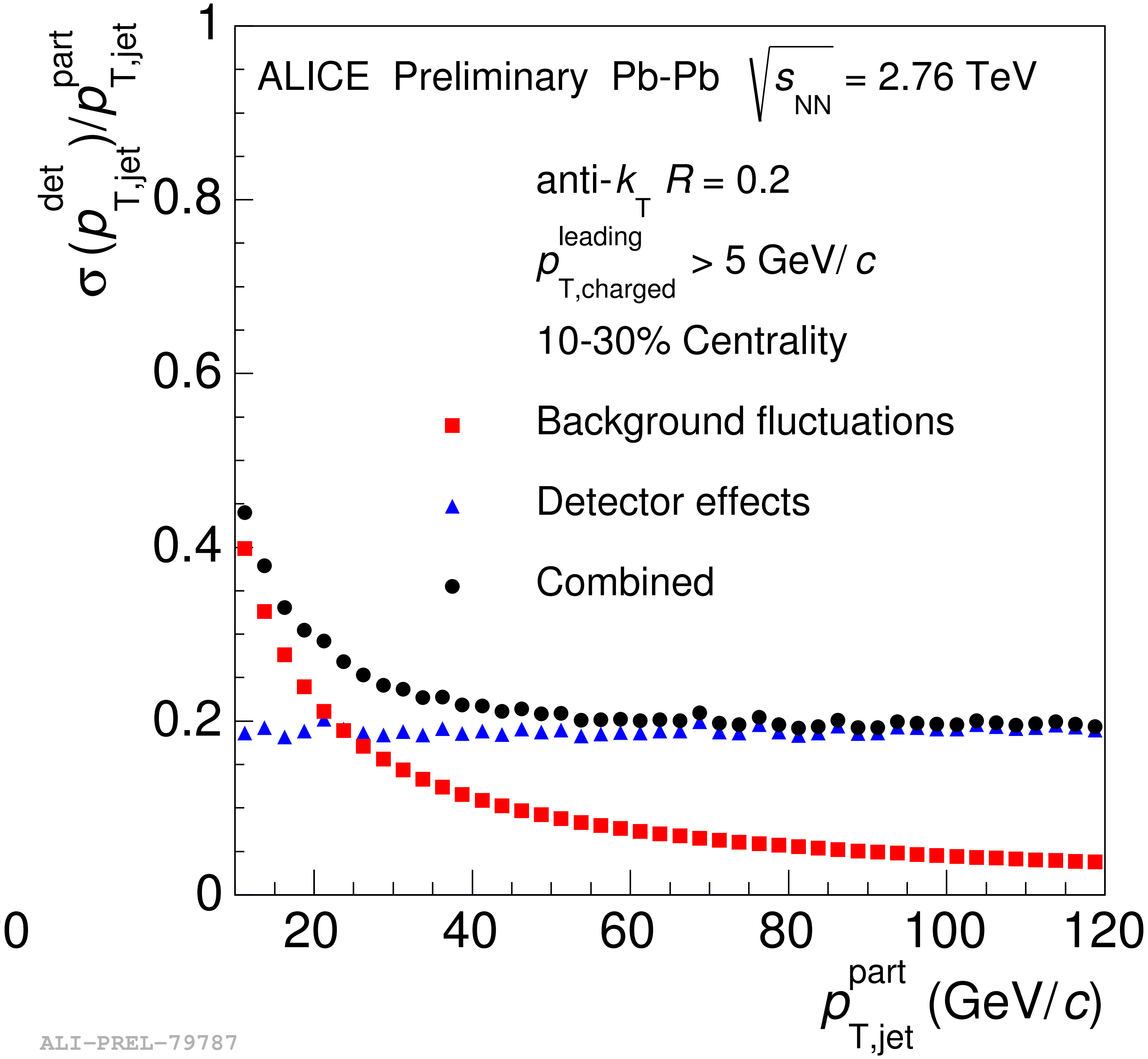
$p_{T,det}$: detector level jet p_T

- Detector effect: obtained by PYTHIA+realistic detector simulations
  - detector resolution — response matrix
  - jet reconstruction efficiency — dominated by the single track efficiency of the leading hadron

➡ multiplicity dependence is determined by Hijing simulations

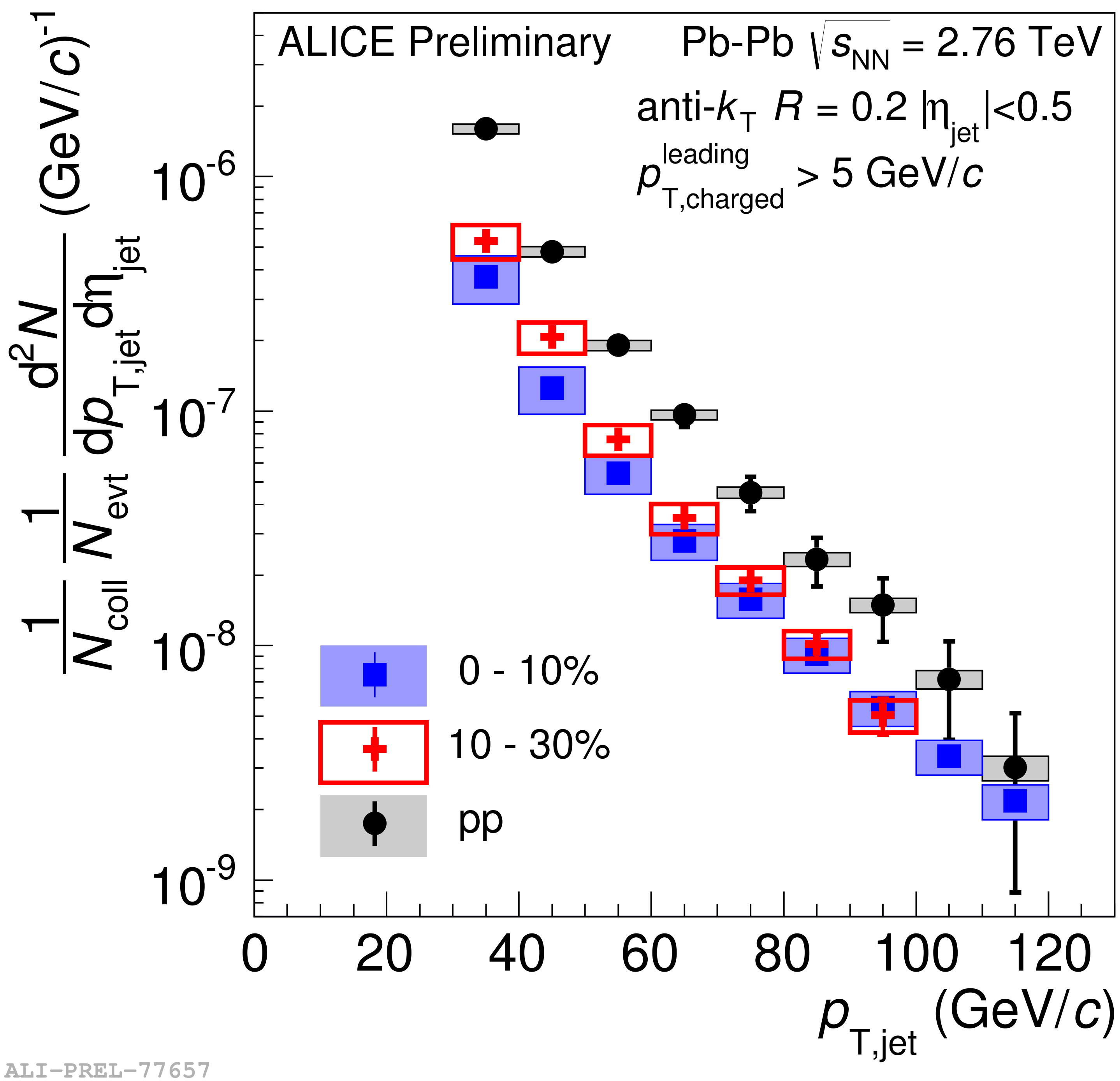
Jet Momentum Resolution





- Background fluctuations: smaller in semi-central collisions (10-30%) than in central collisions (0-10%), dominate in p_T<30 GeV/c
- Detector effects: independent of centrality and p_T, dominate in p_T>30 GeV/c

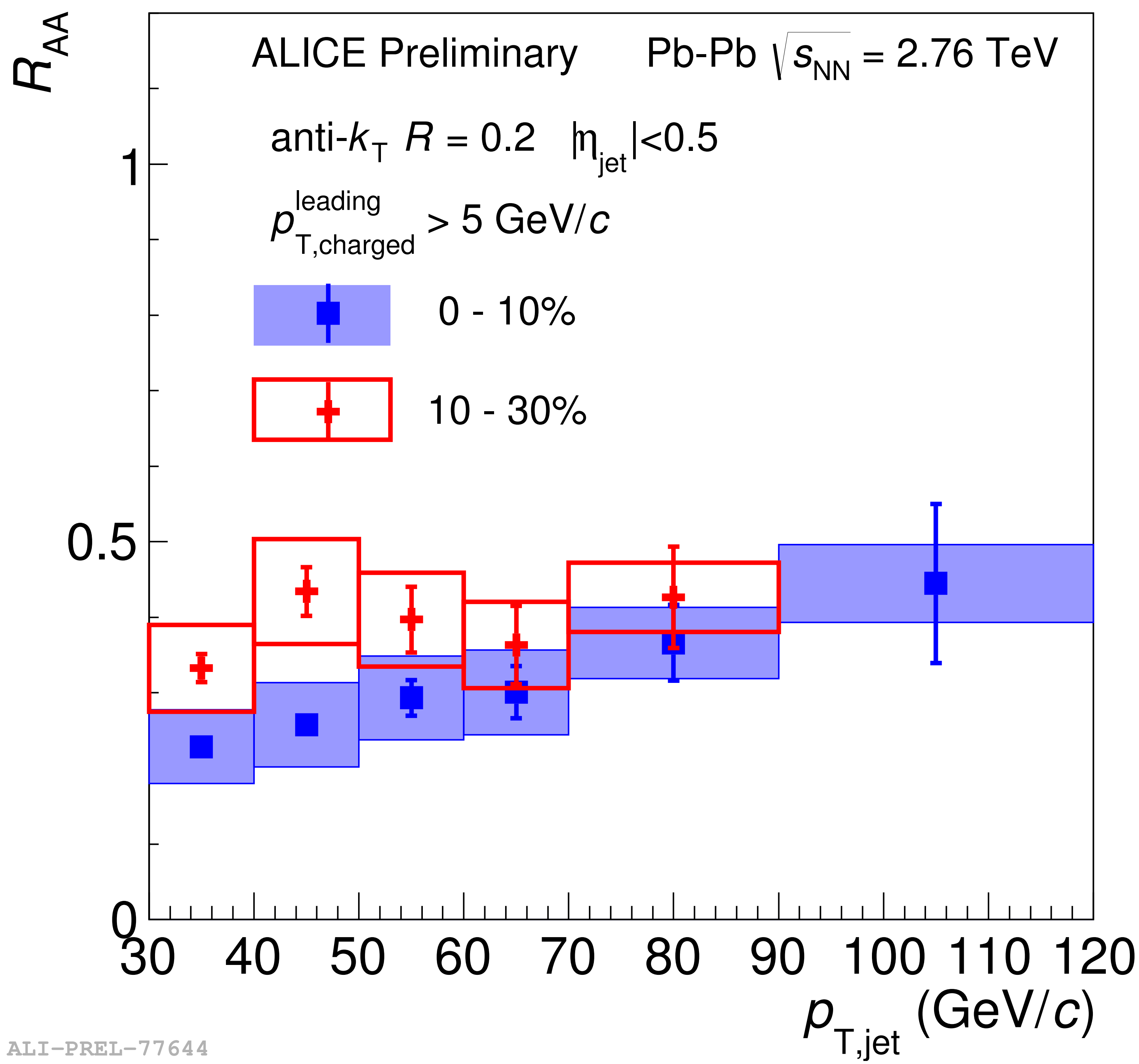
Jet p_T Spectra at Particle Level

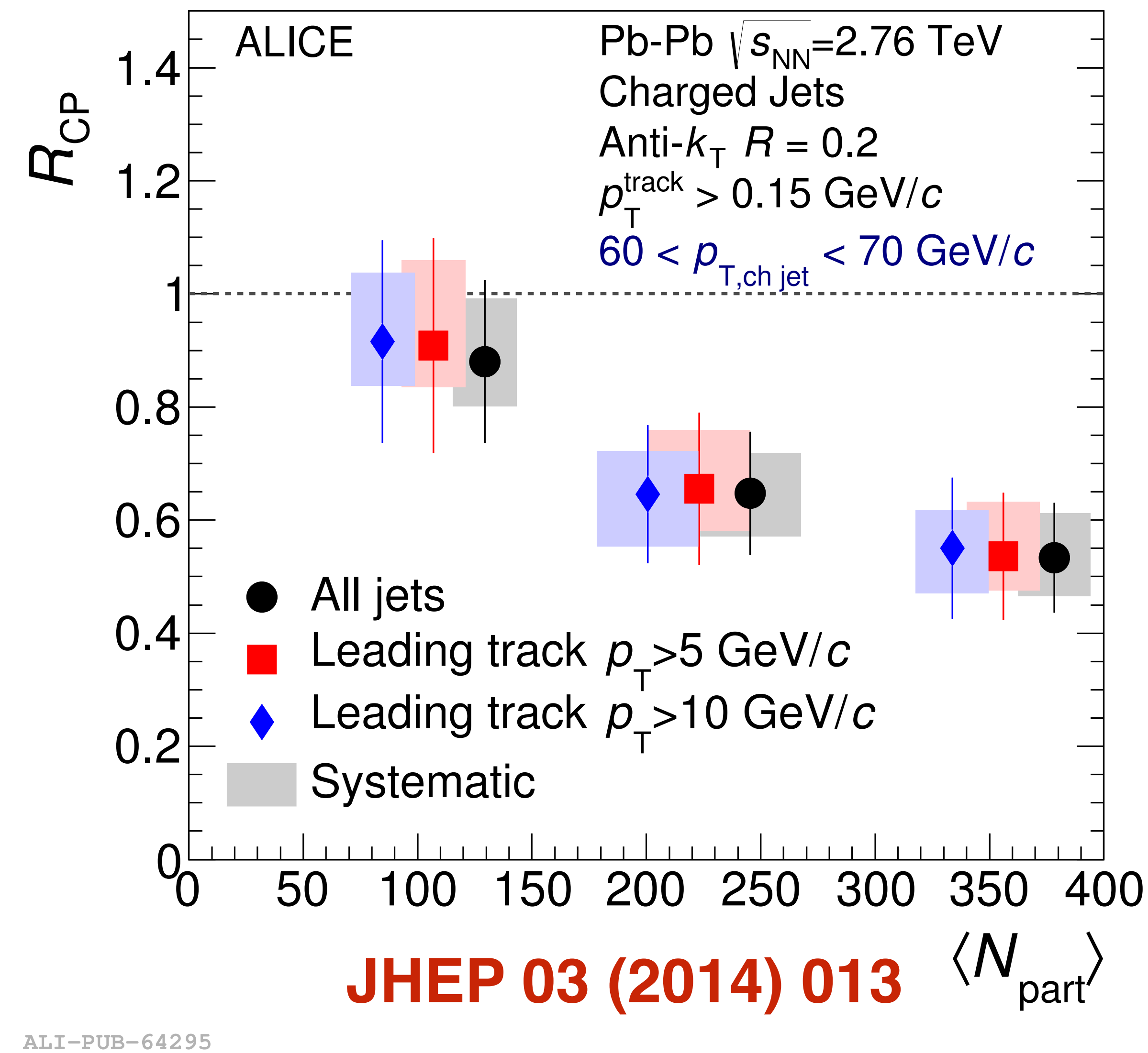


- Corrections applied for both detector effects and background fluctuations through unfolding
- Unfolding methods
  - Pb–Pb: SVD, Bayesian, χ^2
  - pp: Bayesian, bin-by-bin

Results
Pb–Pb Collisions

Nuclear Modification Factor

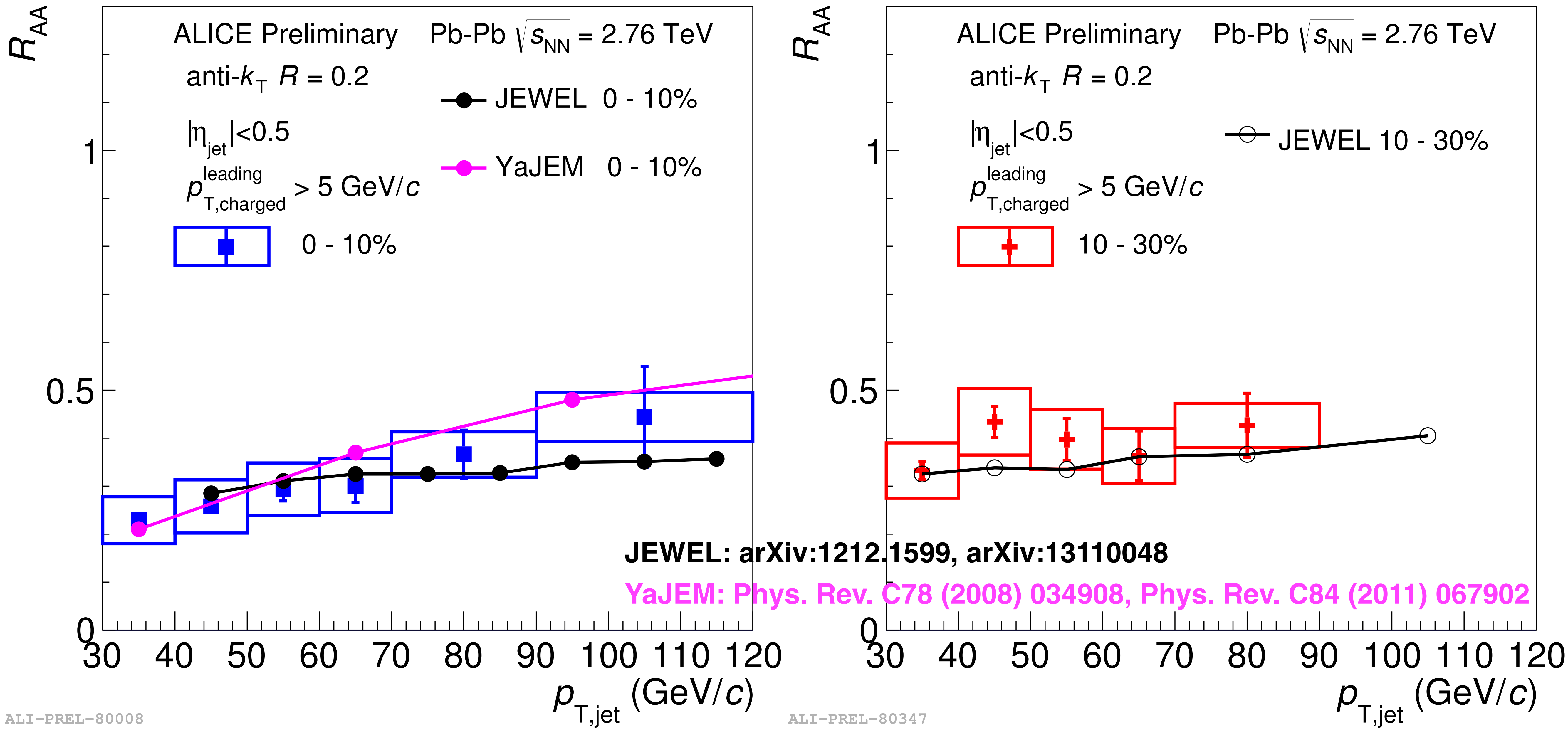




- Consistent with ALICE published results on charged jet R_{CP}

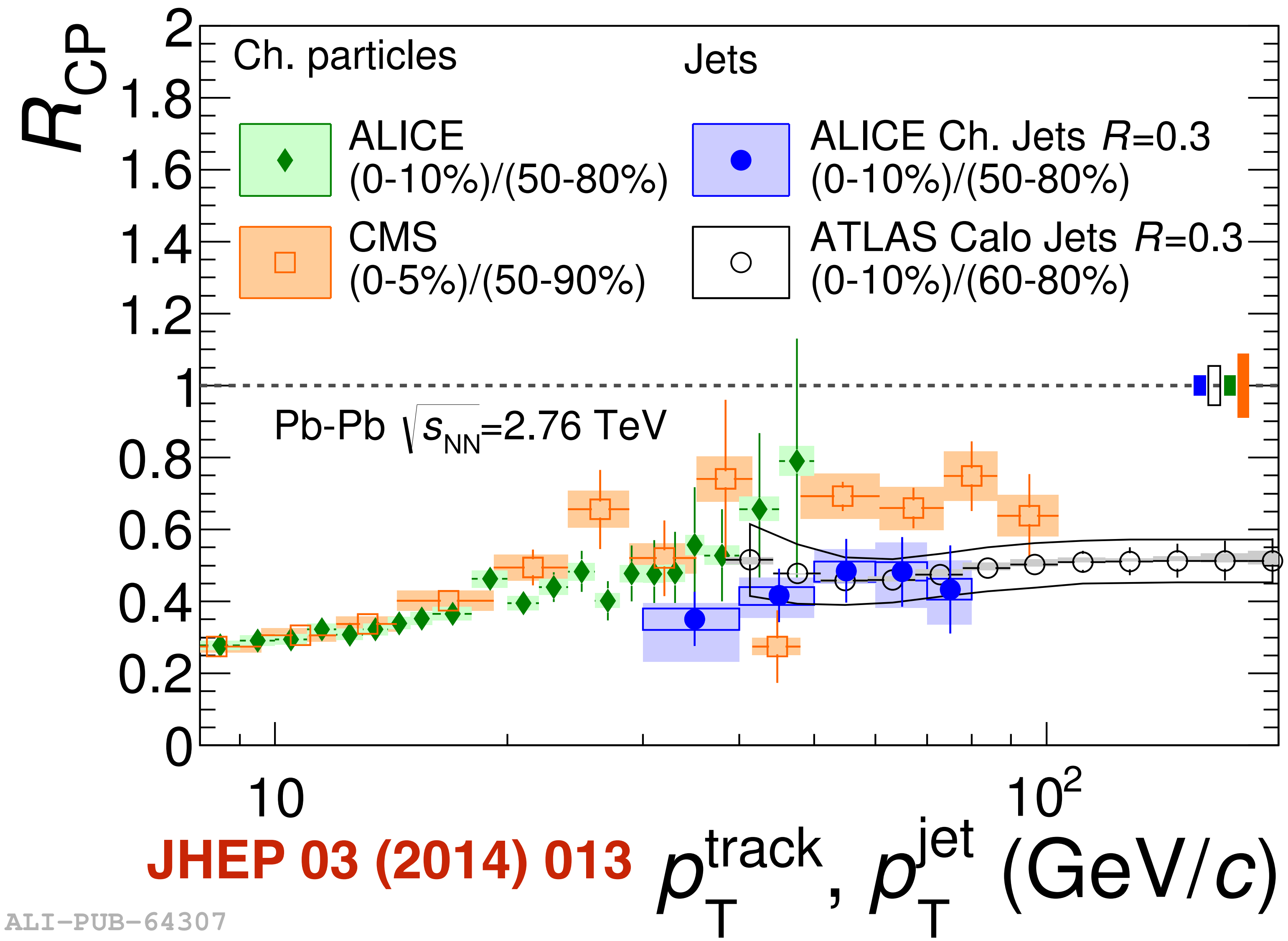
- Strong jet suppression observe dependence on centrality class

Comparison with Theoretical Models



- Good agreement between data and models within errors
  - both models fitted to the single particle R_{AA}

Comparison with ATLAS and CMS



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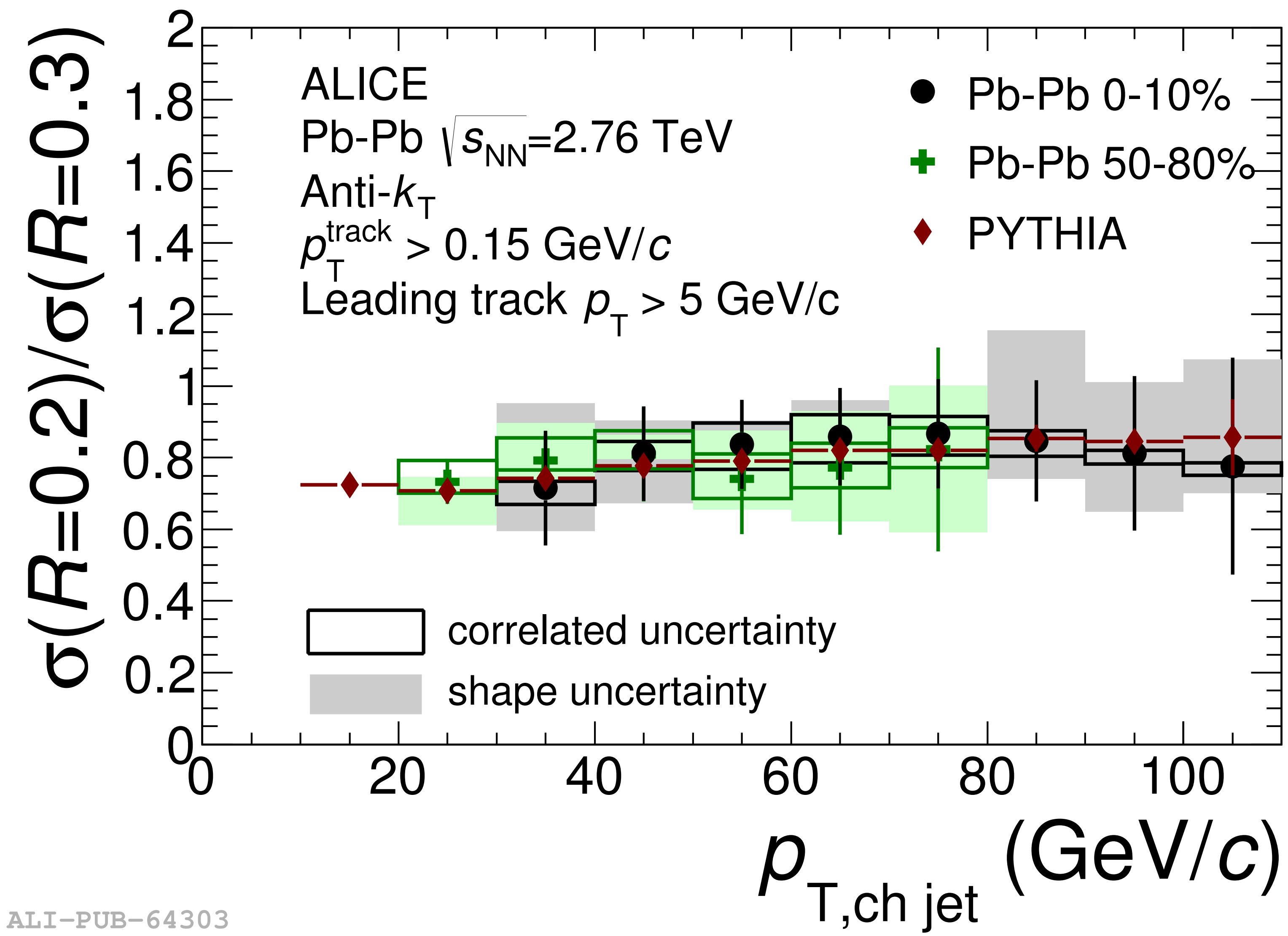
- ATLAS: calorimetric jets
- ALICE: charged particle jets — more sensitive to the low-momentum fragments

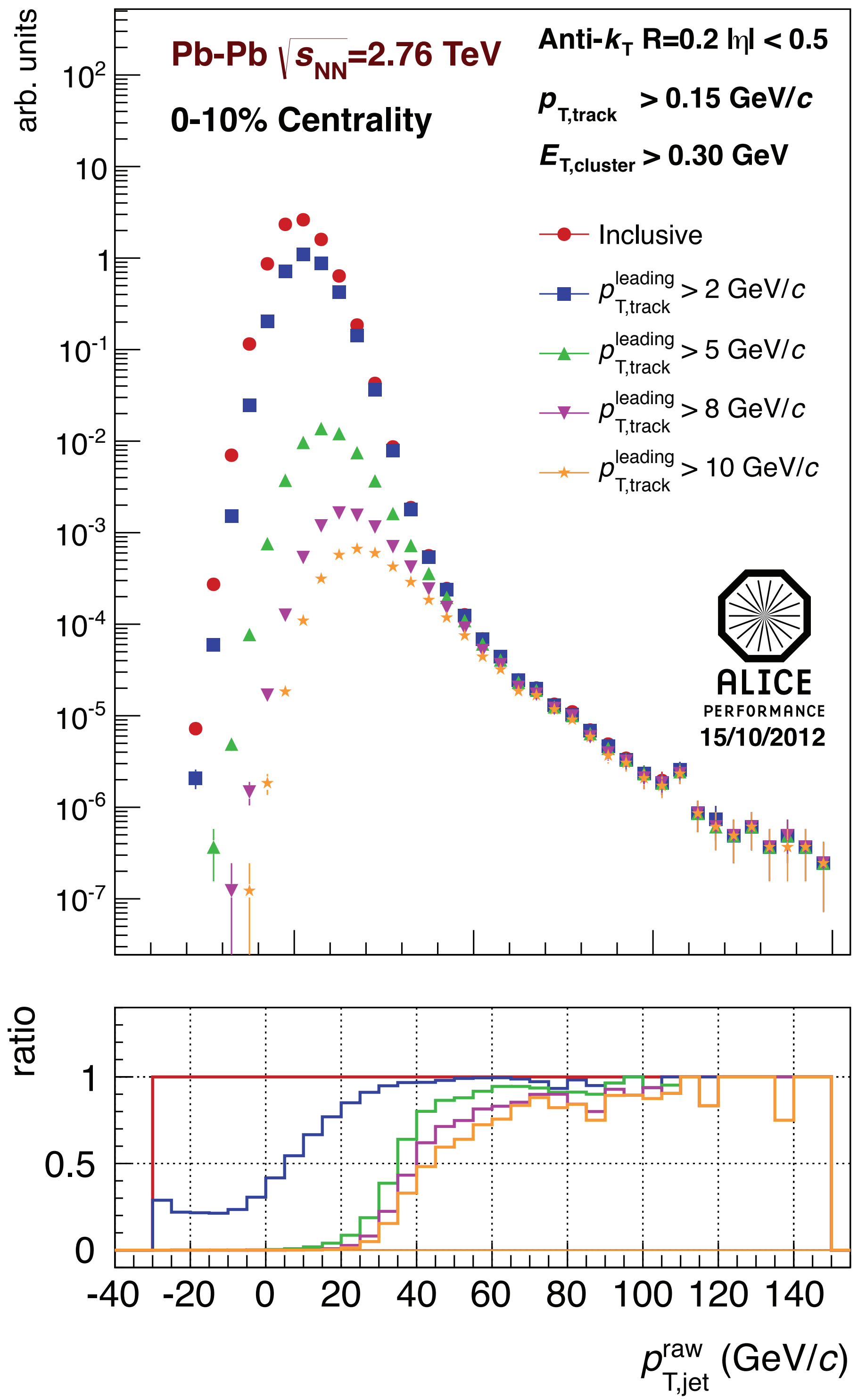
- Agreement between ALICE and ATLAS:
  - contribution of low momentum jet fragments to jet energy is small
- R_{CP} for jets and single hadrons are similar:
  - indicates the momentum is redistributed to larger angles

Ratio of Jet Spectra



- Charged jet ratio consistent with vacuum jets (PYTHIA) and no centrality dependence
  - no evidence of jet structure modification in cone
  - understanding jet quenching requires well developed models

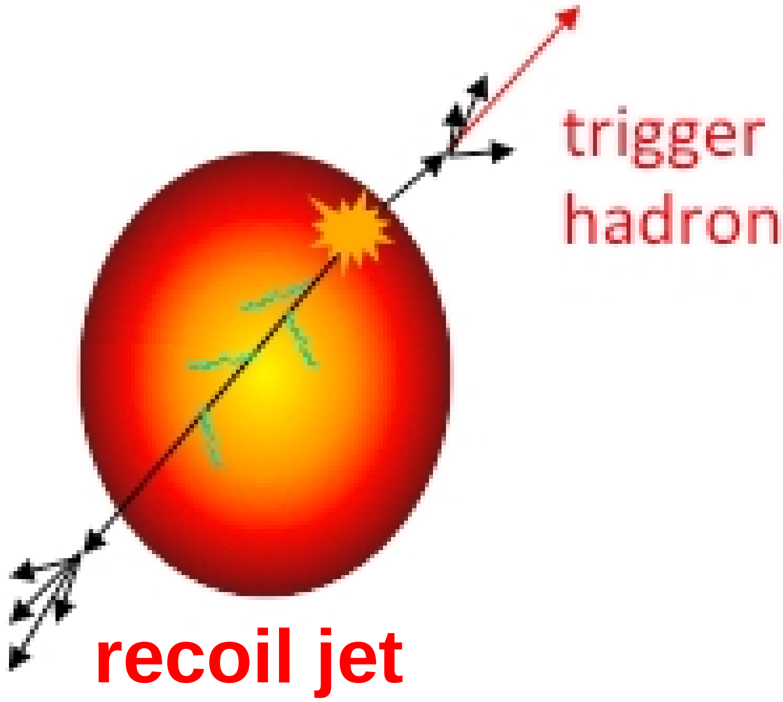
Again: Background



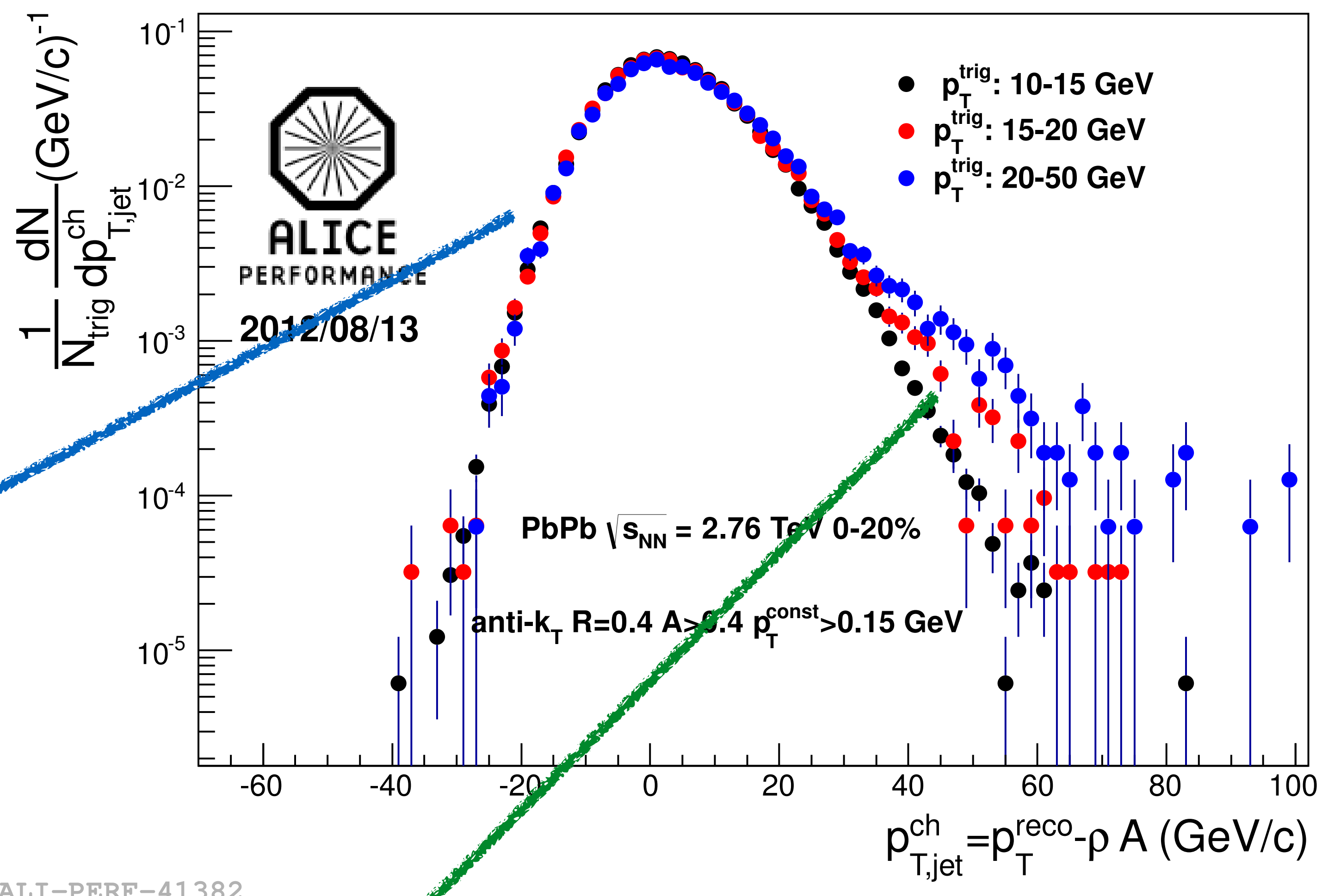
ALI-PERF-44496

- Challenge in heavy-ion collisions
  - large combinatorial background and background fluctuations
  - leading track cut: suppress combinatorial jets — surface bias
  - small jet radius: decrease the background fluctuations — missing redistributed energy

Semi-inclusive Recoil Jet Distribution



- Hadron triggered recoil jet spectrum: minimal surface and fragmentation bias dow to low p_T



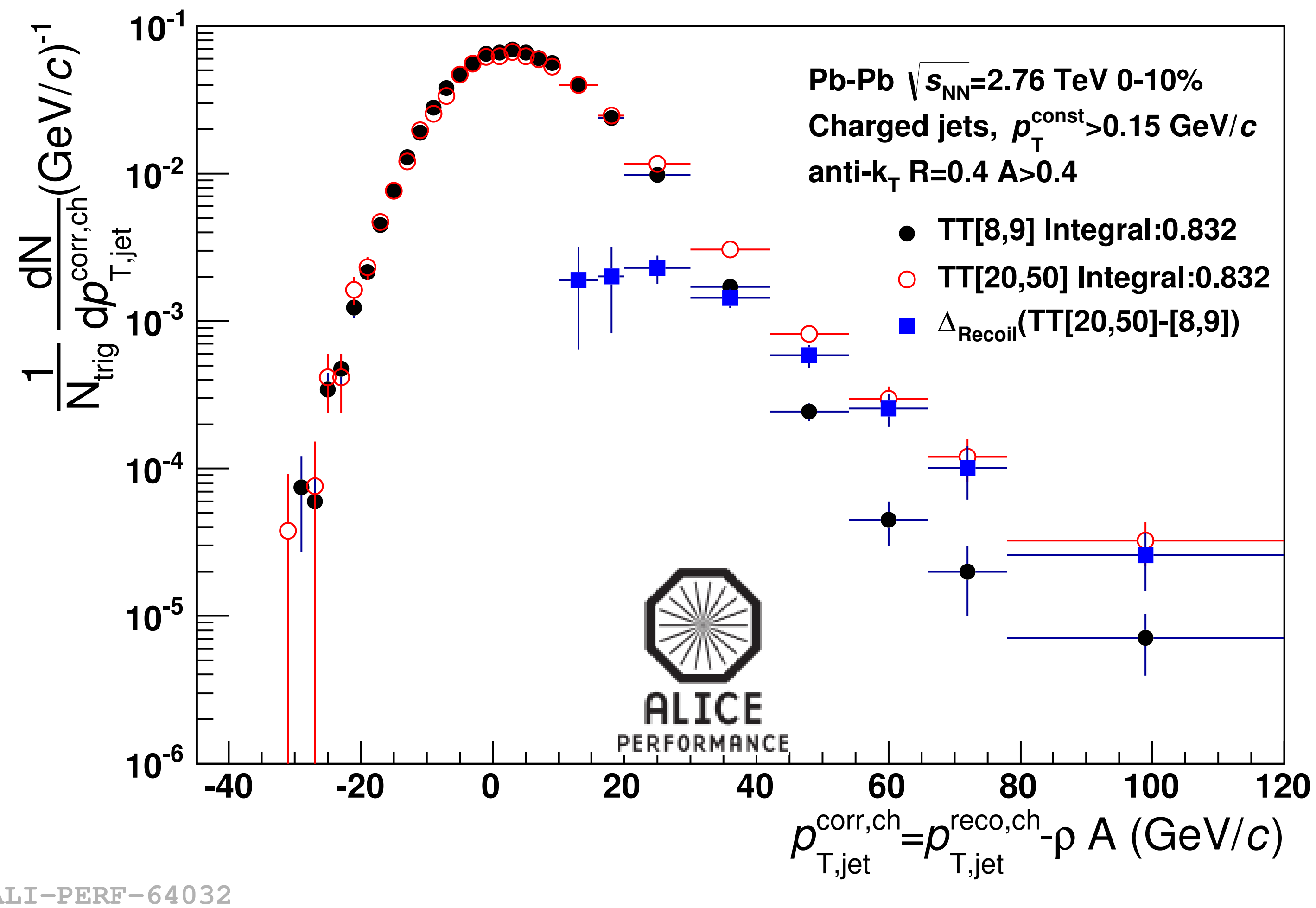
- Dominated by combinatorial jets — uncorrelated with trigger hadron p_T

- Recoil jet spectrum — evolves with trigger hadron p_T

Δ_{recoil} Distribution

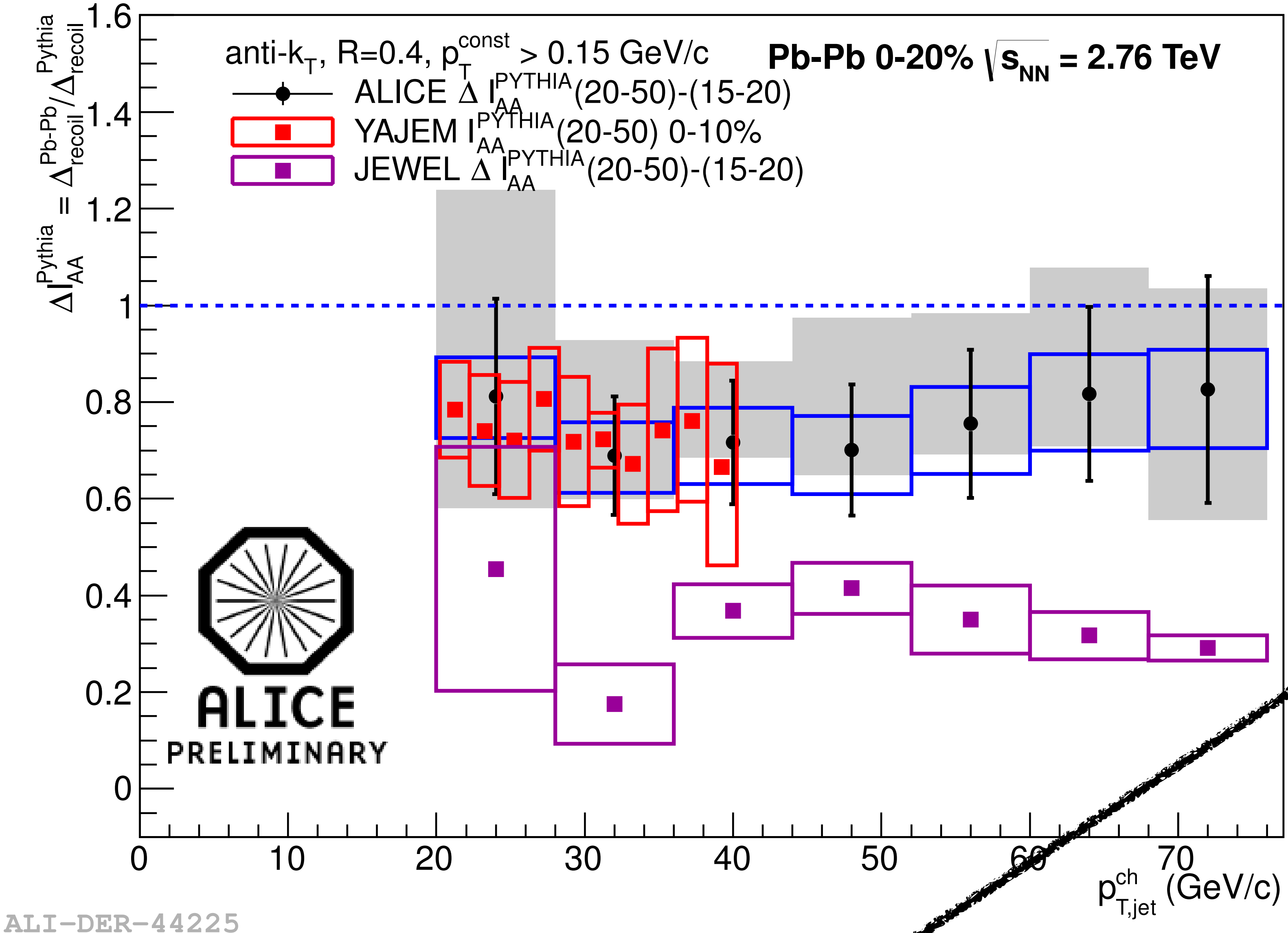
- Opportunity: remove combinatorial background by considering the difference of the recoil jet spectra for two exclusive hadron trigger intervals

$$\Delta_{\mathrm{recoil}} = [1/N_{\mathrm{trg}} \mathrm{d}N/\mathrm{d}p_{\mathrm{T,jet}}]_{\mathrm{trg}} - [1/N_{\mathrm{ref}} \mathrm{d}N/\mathrm{d}p_{\mathrm{T,jet}}]_{\mathrm{ref}}$$



- Δ_{recoil} is clean of the combinatorial background
- still has to be corrected for background smearing of jet energy and detector effects

Recoil Jet ΔI_{AA}

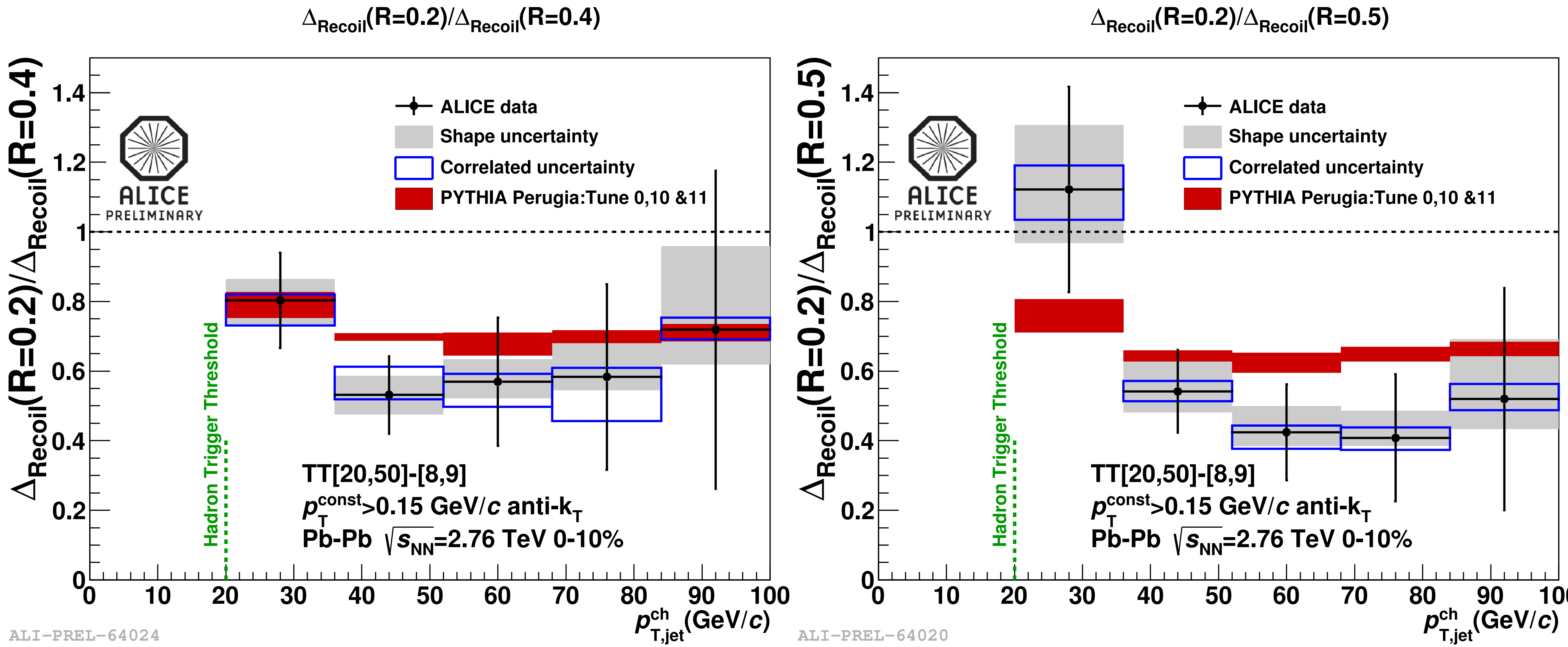


$$\Delta I_{AA}^{\mathrm{Pythia}} = \Delta_{\mathrm{recoil}}^{\mathrm{Pb-Pb}} / \Delta_{\mathrm{recoil}}^{\mathrm{Pythia}}$$

- YAJEM: agree with data
- JEWEL: $\Delta I_{AA} \sim 0.4$ below the measurement

- Difference in energy loss mechanism or modeling collision/medium?

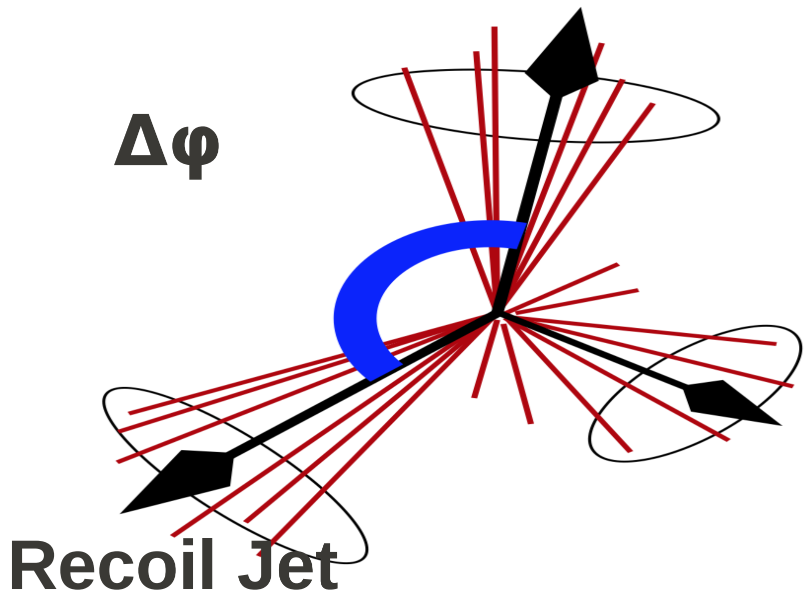
Ratio of Recoil Jet Yield

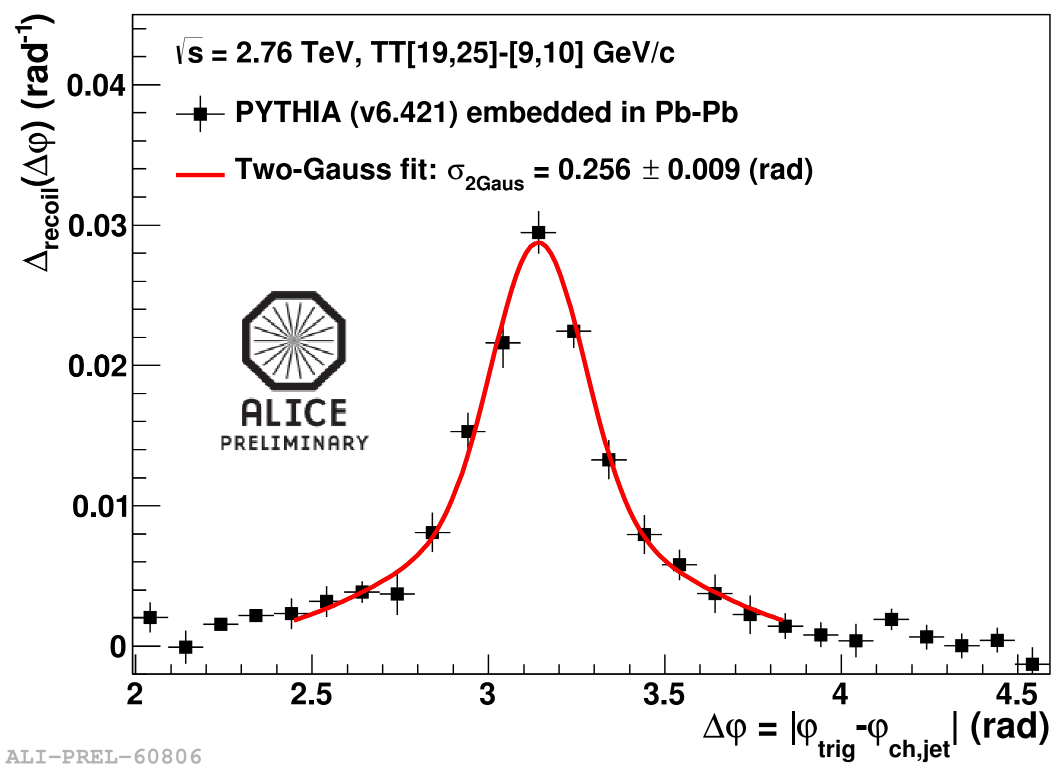


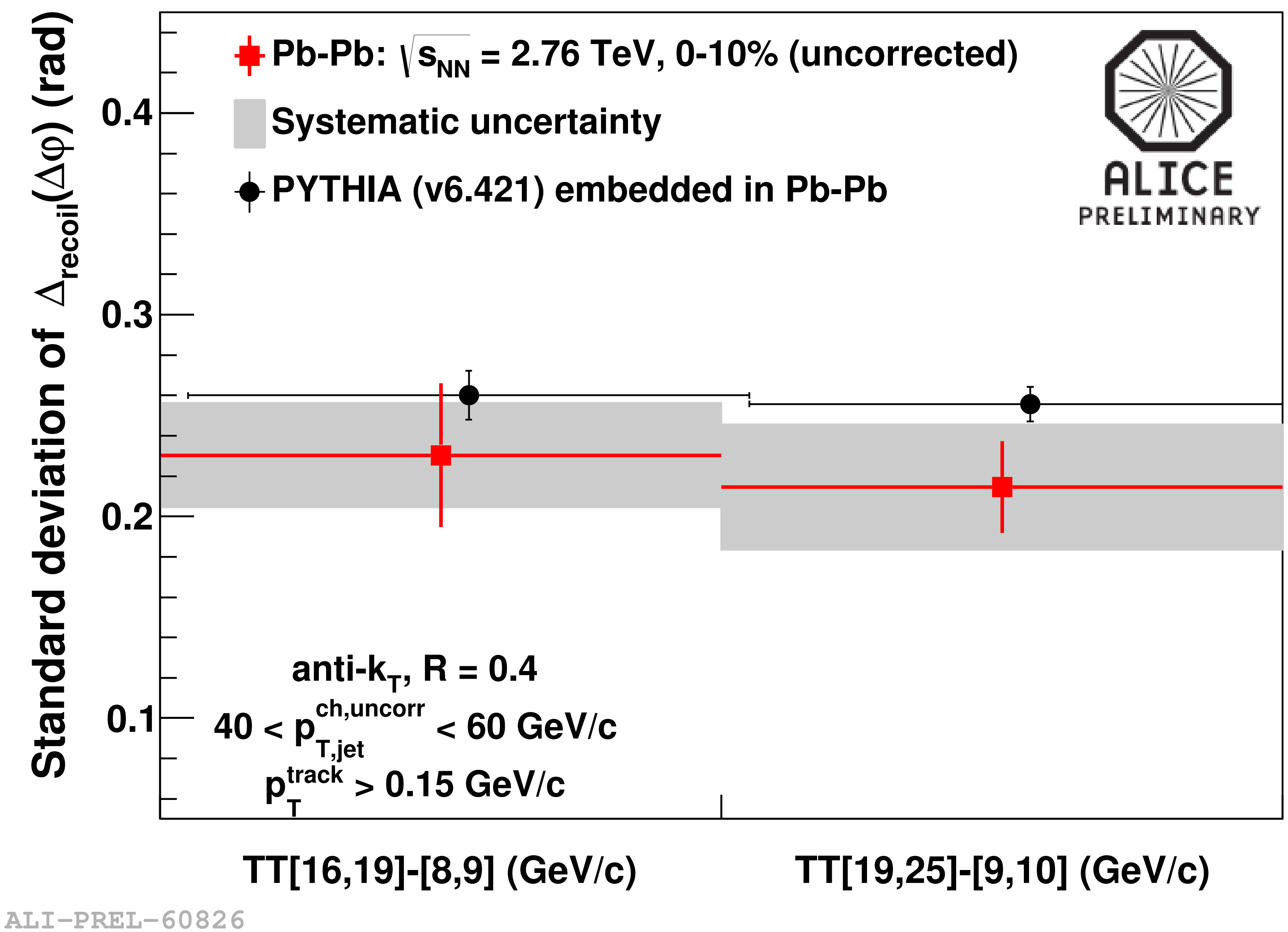
- $\Delta_{\mathrm{recoil}}(R=0.2)/\Delta_{\mathrm{recoil}}(R=0.4)$: no evidence for significant energy redistribution within R=0.4
- $\Delta_{\mathrm{recoil}}(R=0.2)/\Delta_{\mathrm{recoil}}(R=0.5)$: data systematically below PYTHIA (in jet p_T>36 GeV/c) — hint of energy redistribution?

Hadron–Jet Azimuthal Correlation

- Can medium-induced radiation emitted out-of-cone change the jet direction?

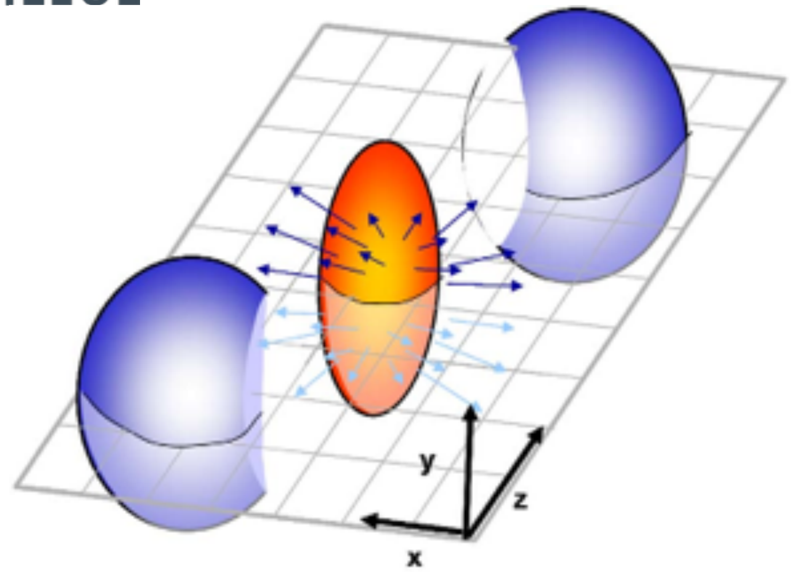




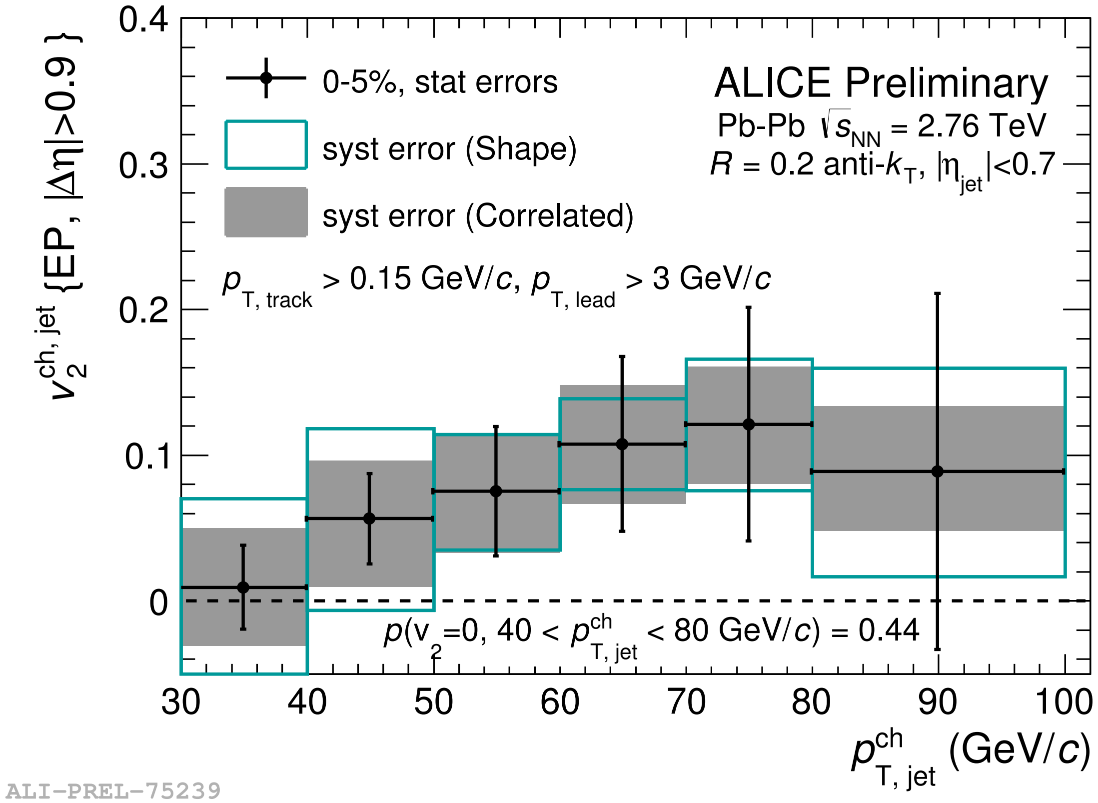


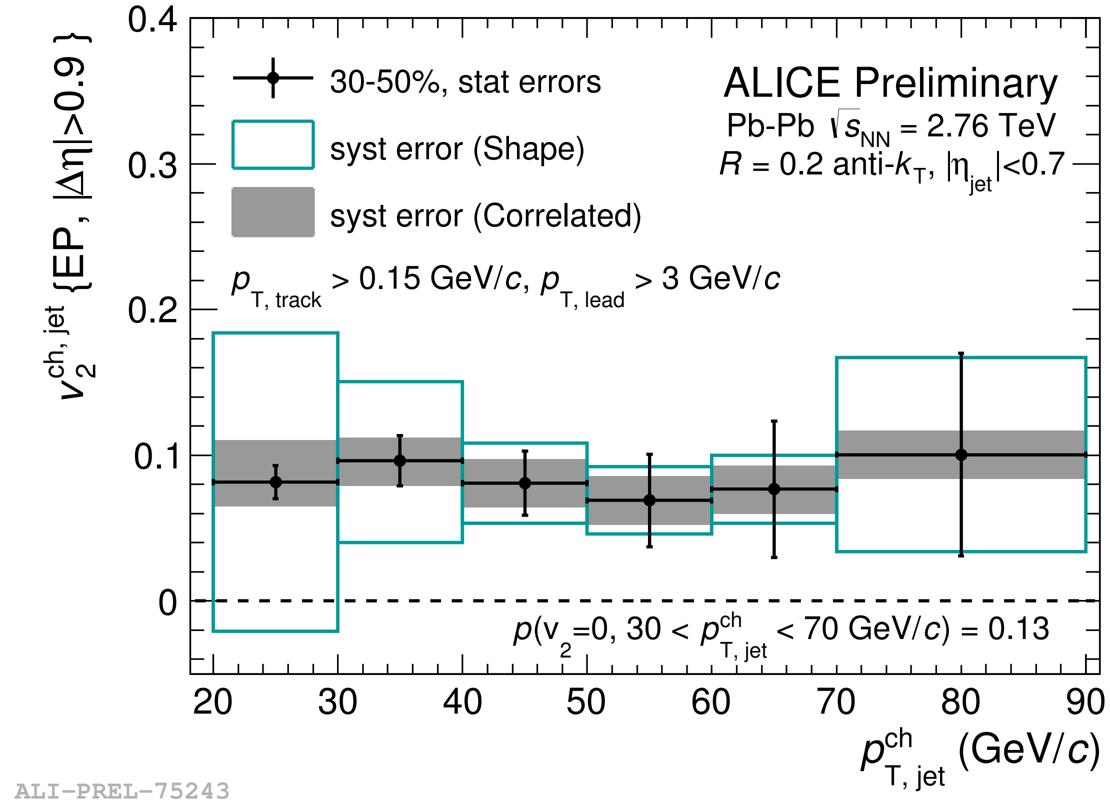
- PYTHIA consistent with data within errors — no evident medium-induced acoplanarity observed for selected kinematics

Event Plane Dependence of Jets



$$v_2^{\mathrm{jet}} = \frac{1}{R_{\mathrm{EP}}}\frac{1}{4\pi}\frac{N_{\mathrm{in}}-N_{\mathrm{out}}}{N_{\mathrm{in}}+N_{\mathrm{out}}}$$

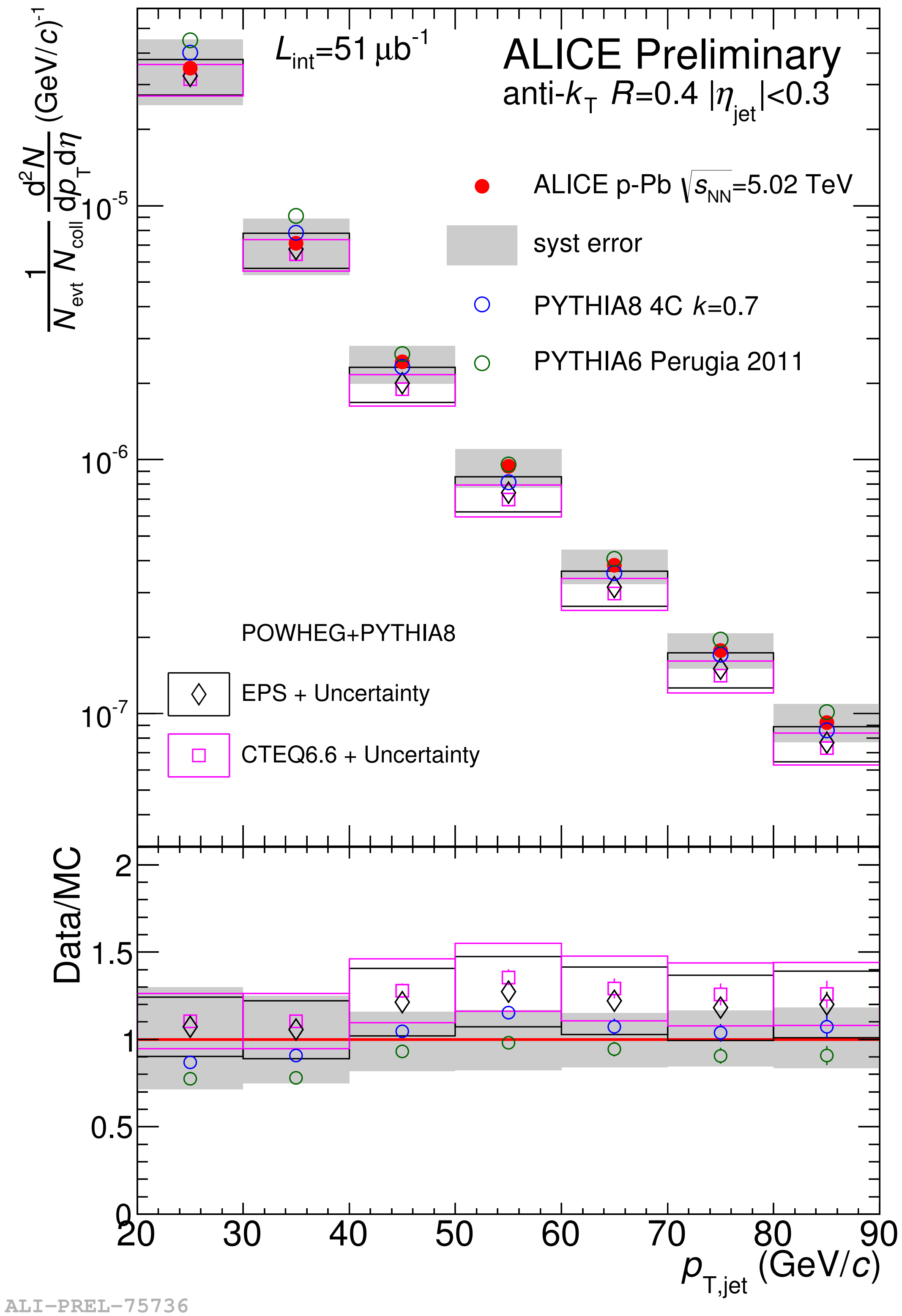




- Used to investigate the path length dependence of jet energy loss
- non-vanished v_2 in semi-central collisions (30-50%) with 2σ effect

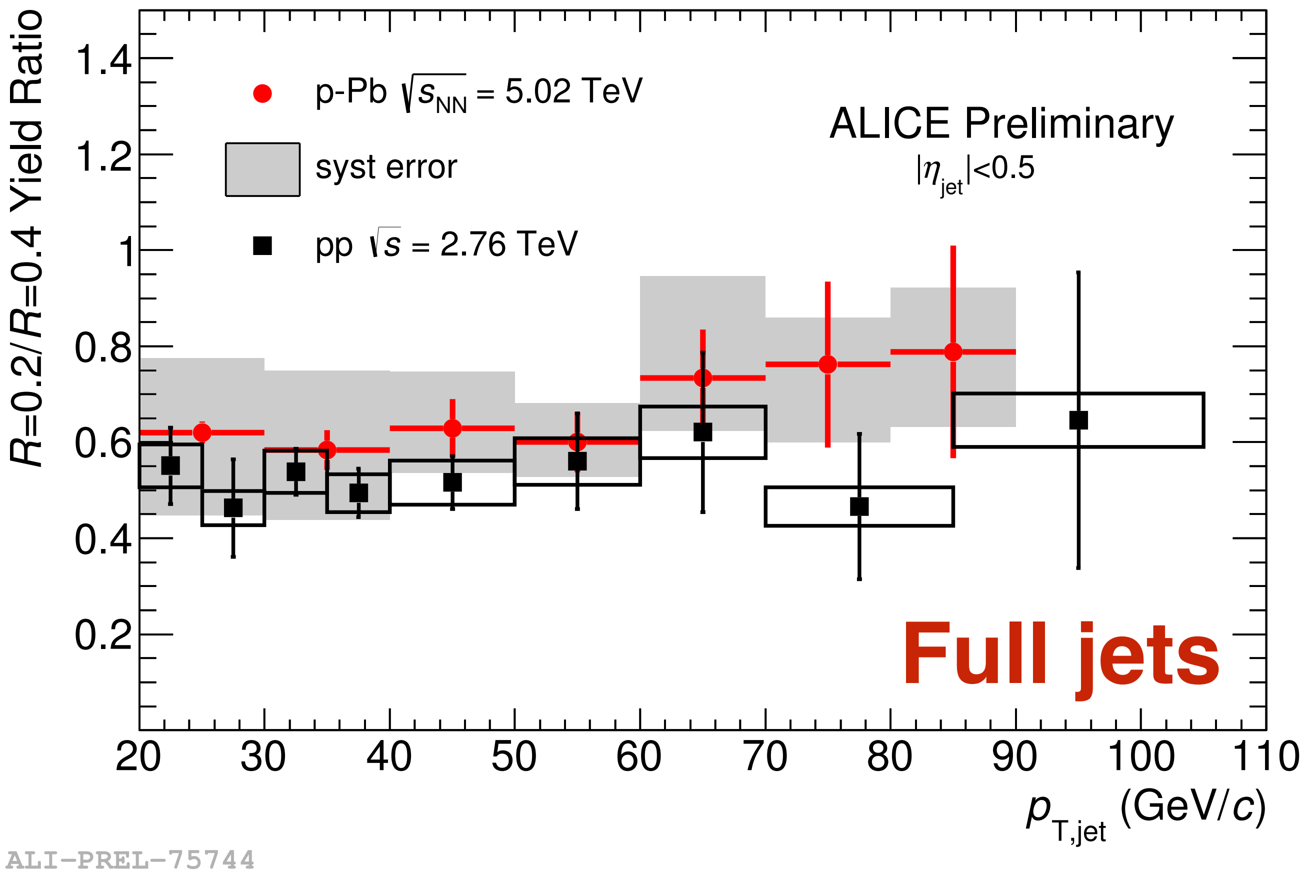
Results
p–Pb and pp Collisions

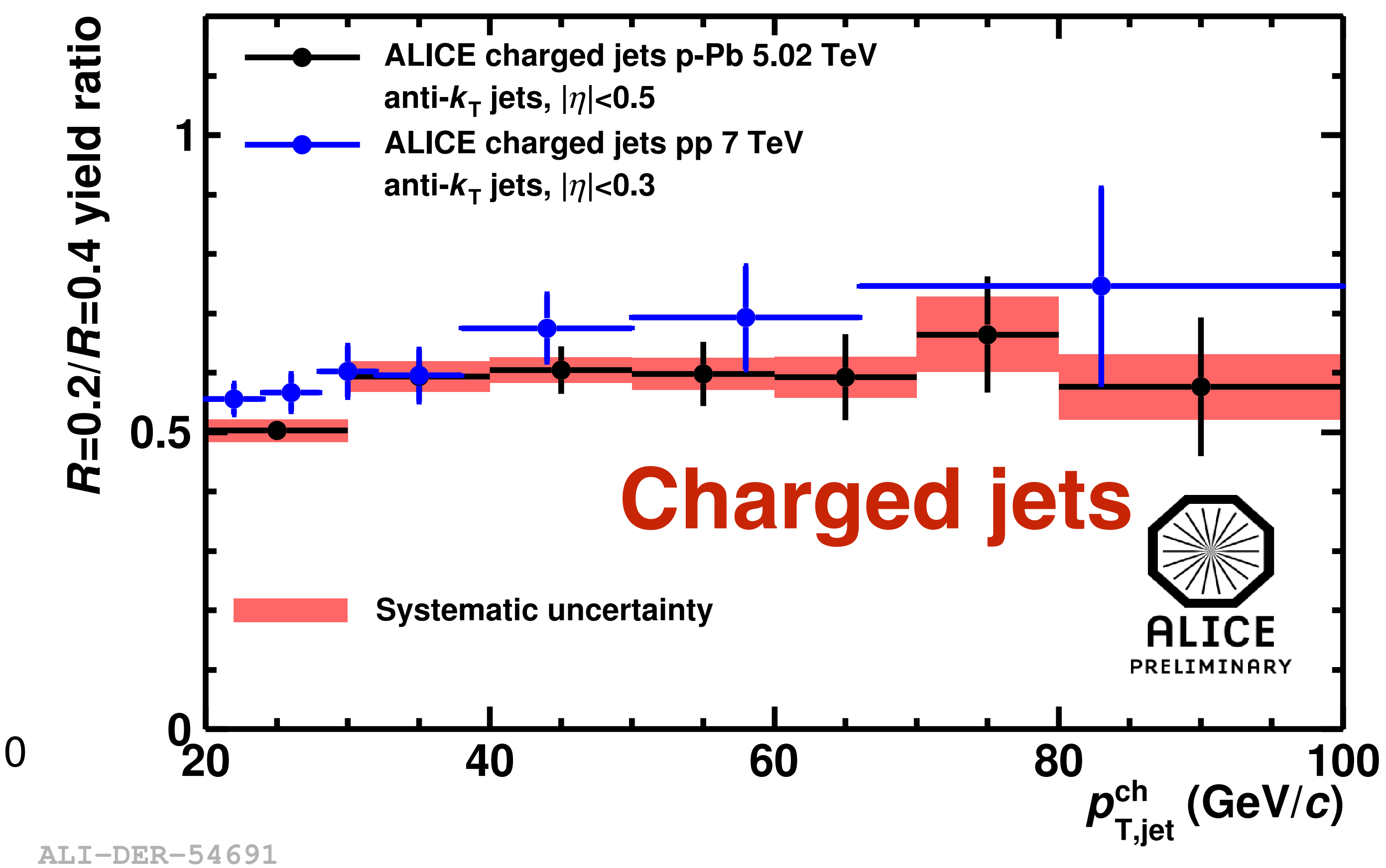
Corrected Jet Spectrum



- Jet measurements in p–Pb collisions
  - crucial test of the cold nuclear effects
  - using the similar techniques as in Pb–Pb collisions
  - background density is corrected by the event occupancy to since the large local fluctuations of the event multiplicity

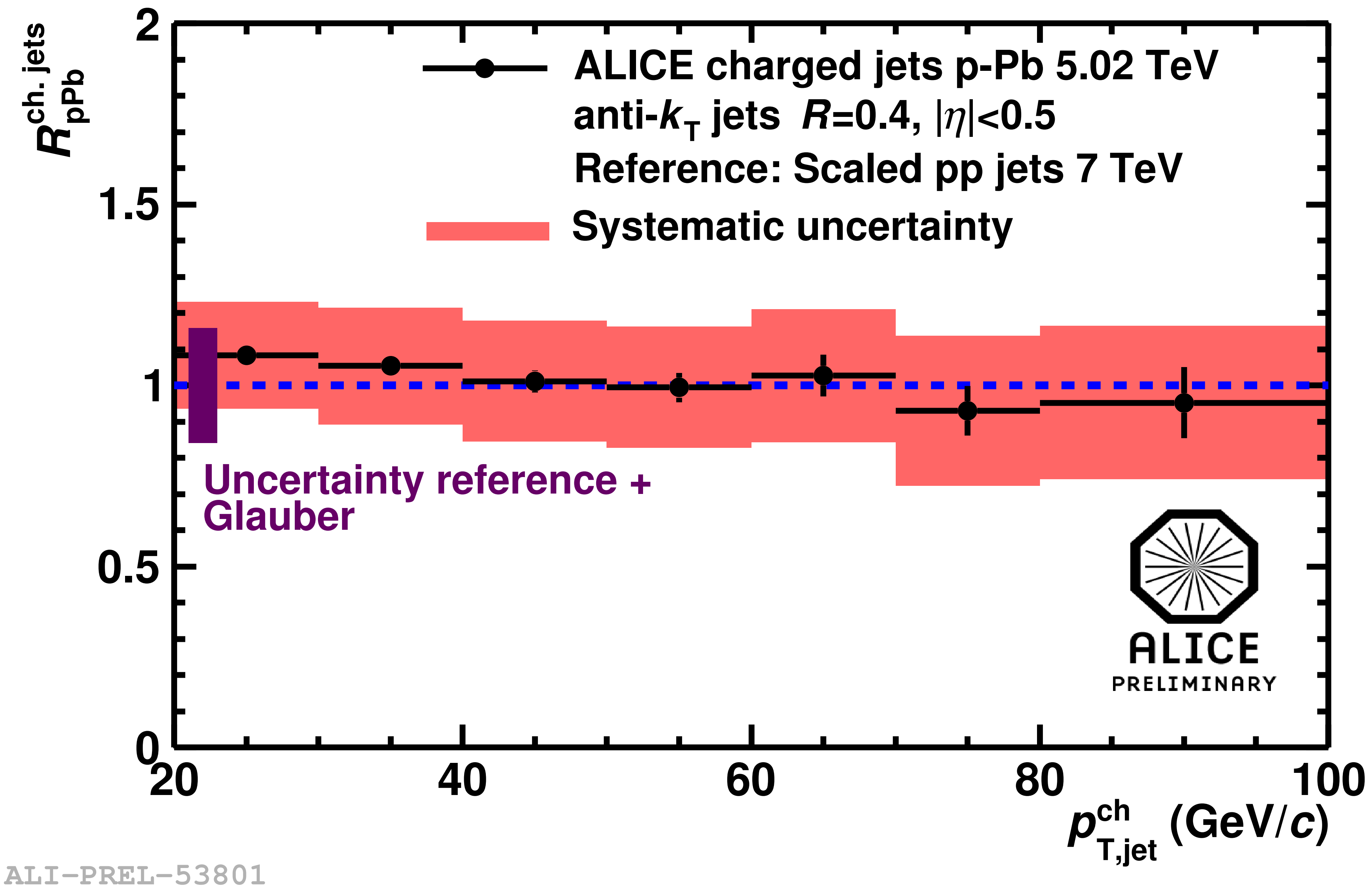
Ratio of Jet Spectra





- Results consistent with no significant cold nuclear effect on jet transverse distribution in R<0.4 in p–Pb collisions
- the same conclusion for both full jets and charged jets

Charged Jets R_{pA}

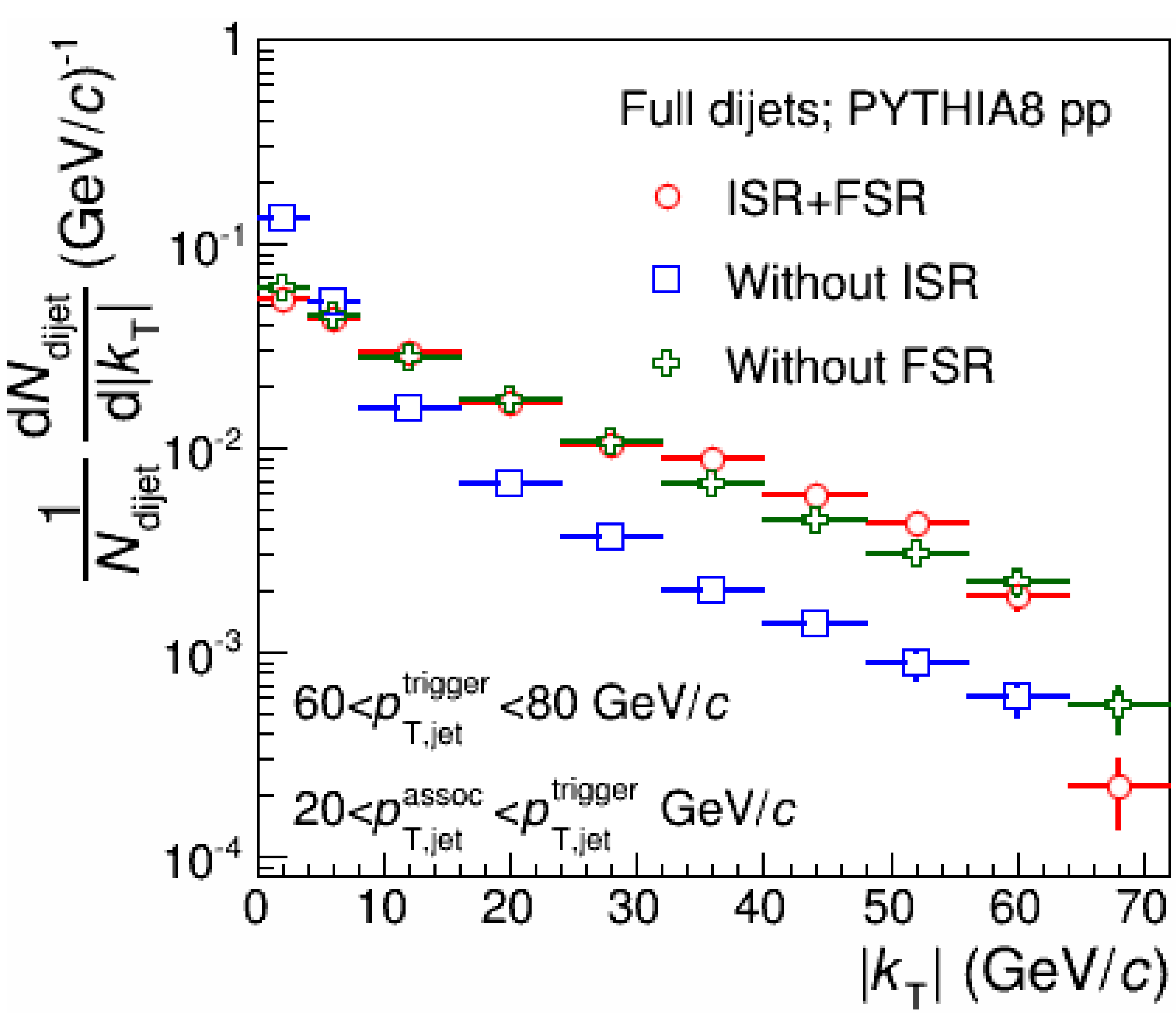


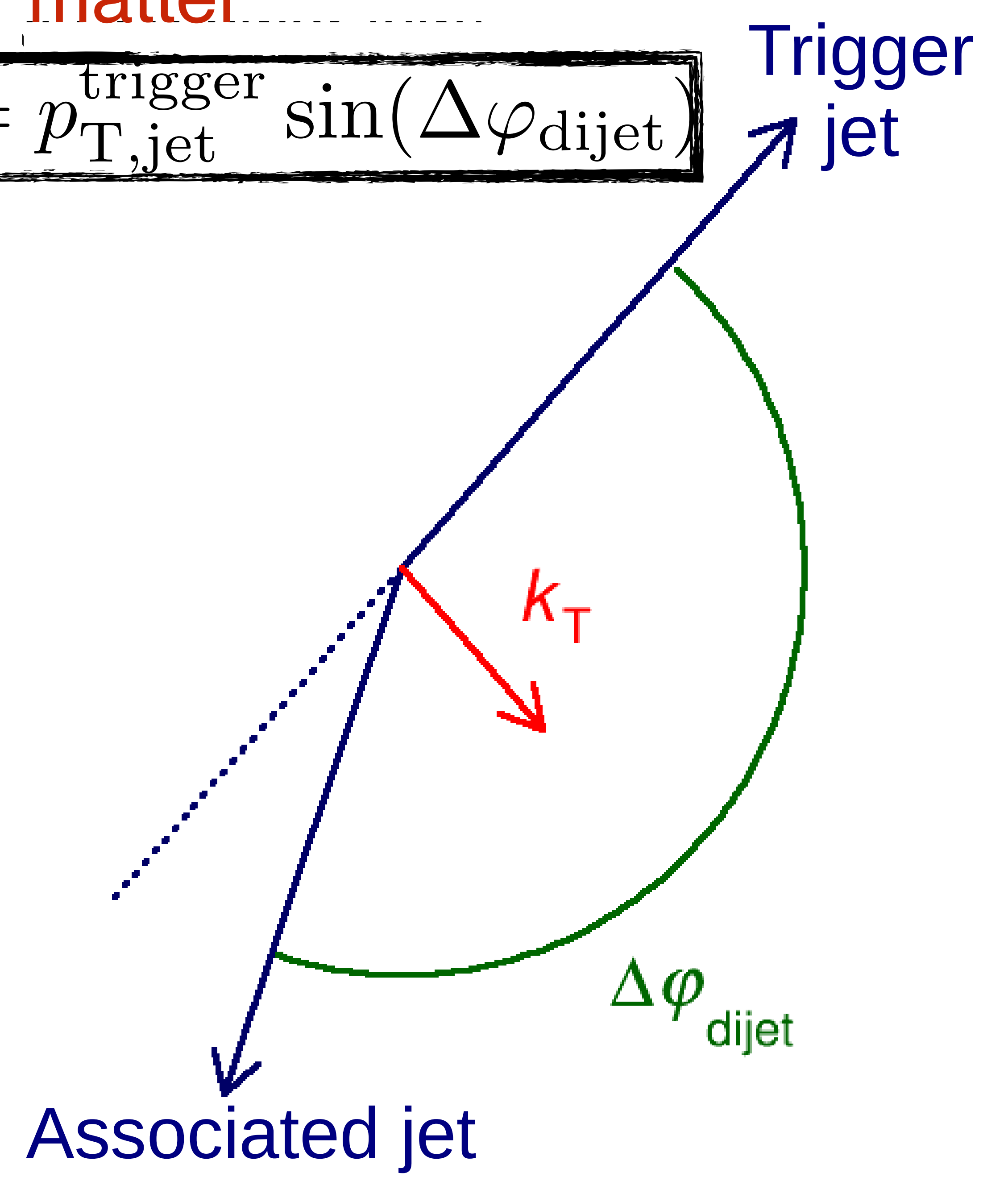
- Results consistent with no significant cold nuclear effect on jet production in p–Pb collisions
  - jet suppression in Pb–Pb final state effect

Dijet k_T in p–Pb Collisions

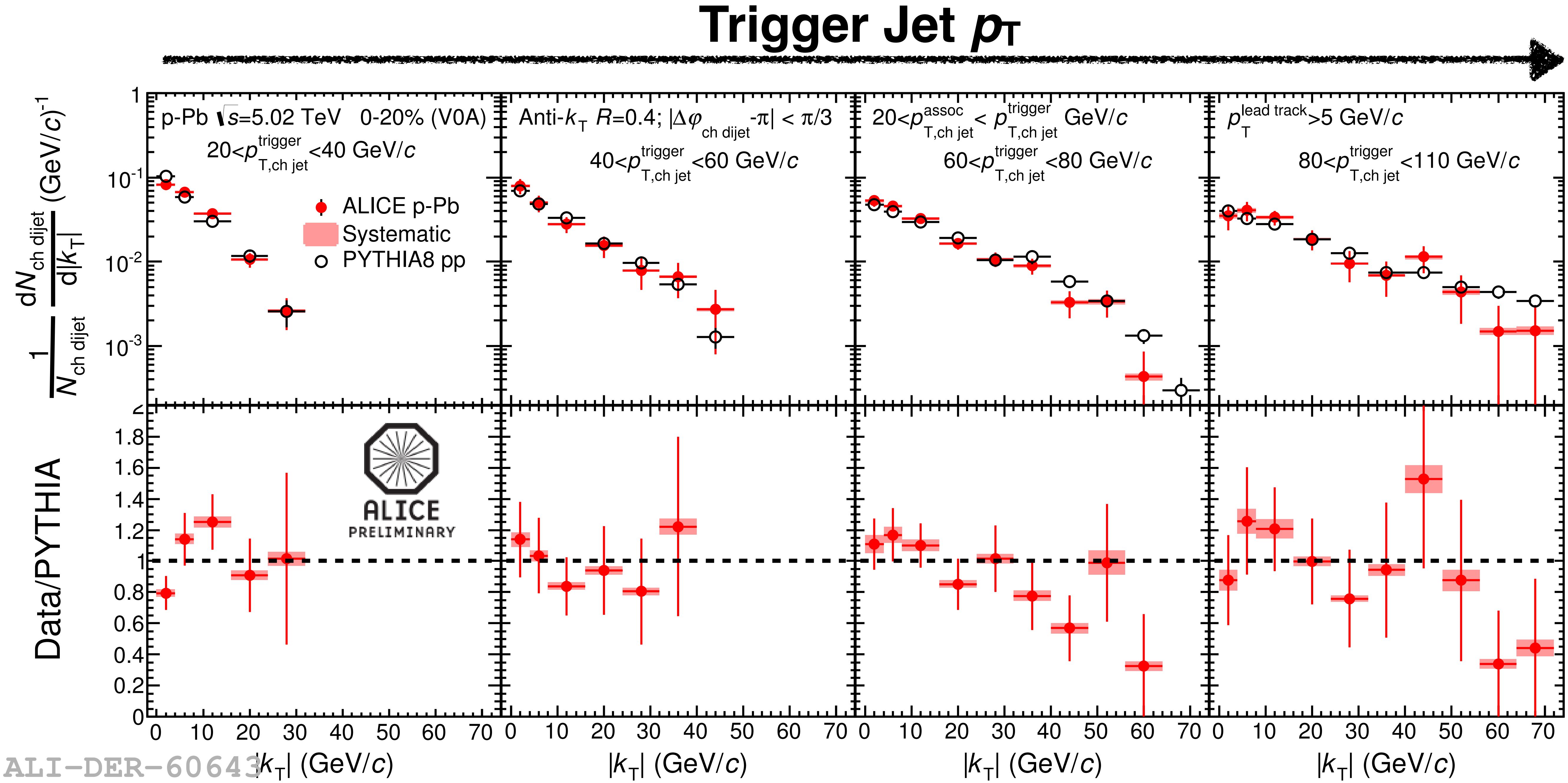
- Dijet k_T in p–Pb collisions
  - intrinsic k_T + initial and final state radiations
  - + scattering of parton in cold nuclear matter

$$k_{\mathrm{T}} = p_{\mathrm{T,jet}}^{\mathrm{trigger}} \sin(\Delta\varphi_{\mathrm{dijet}})$$



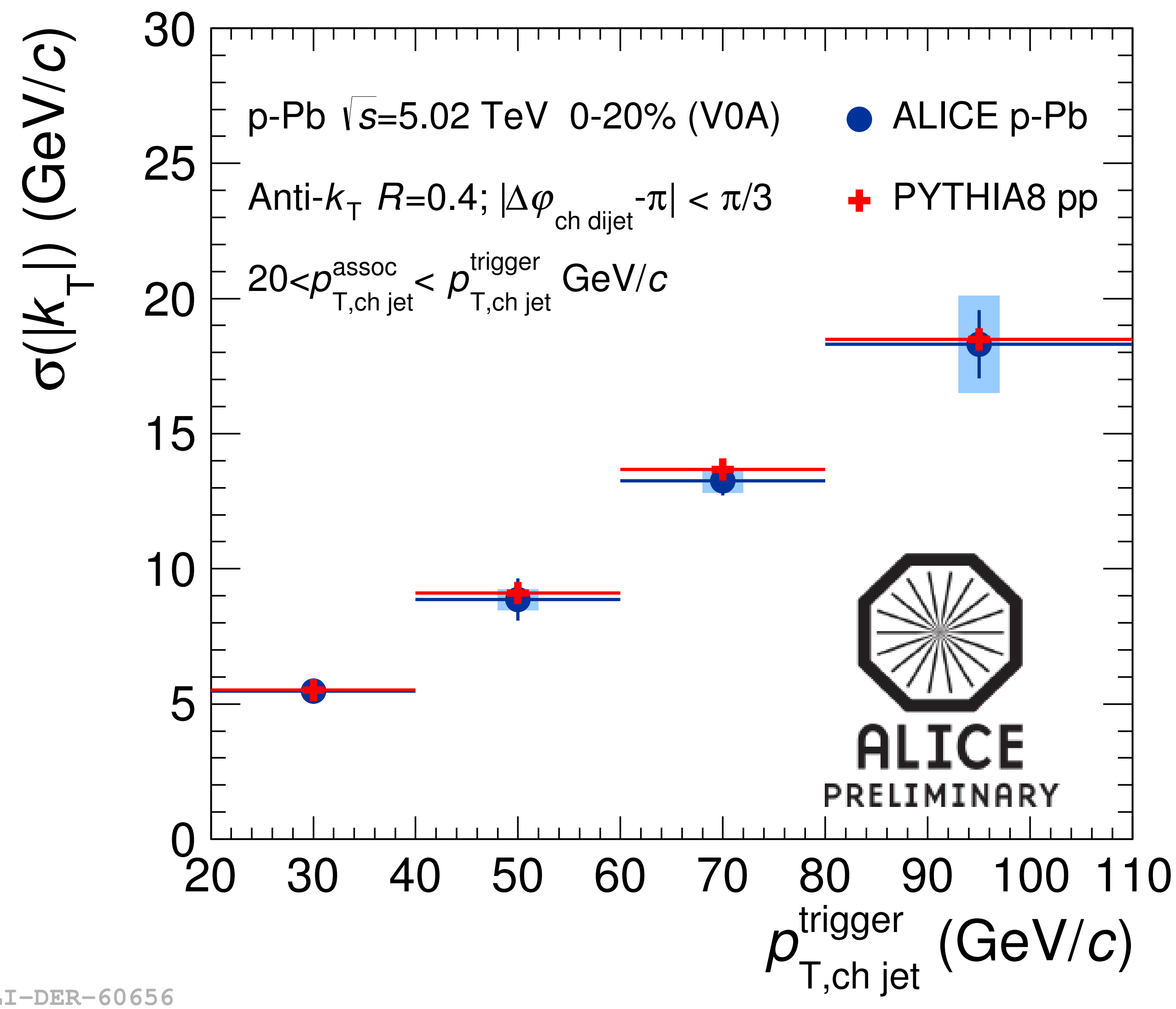


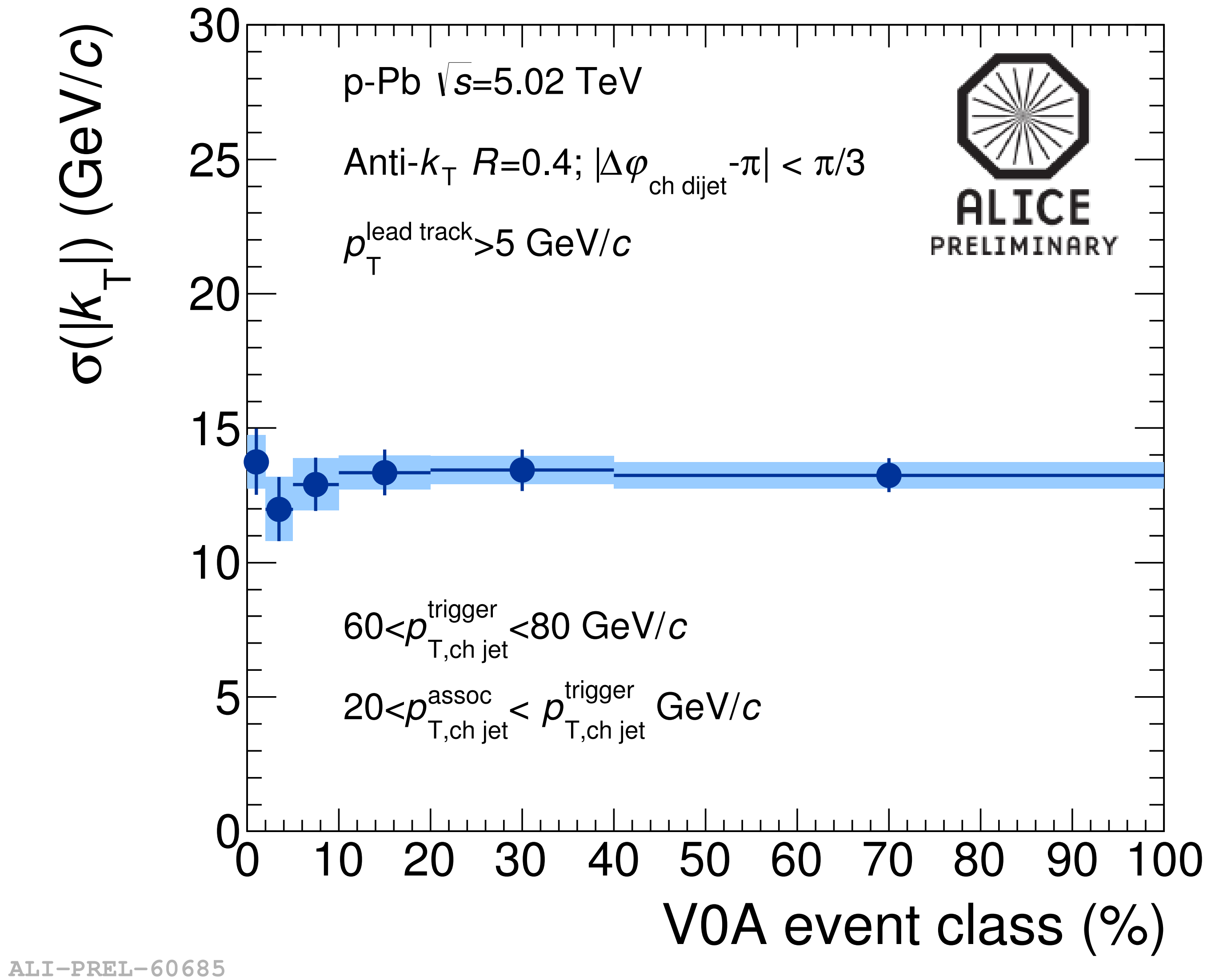
k_T vs. Trigger p_T



- No Significant deviation in data compared to PYTHIA

Dijet k_T Width



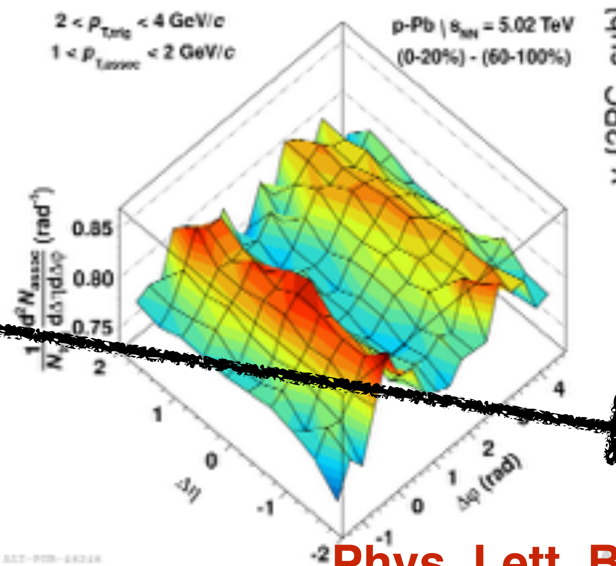


- k_T width increases with trigger jet p_T
  - compatible in data and PYTHIA simulations
- No modification of k_T width observed also in high multiplicity events

Particle Production in p–Pb Collisions

High multiplicity p–Pb and Pb–Pb collisions - similarities

- double ridge structure
- $v_2 > 0$ and PID dependent
- enhanced Λ/K_S^0 ratio
  - ➡ involving several phenomena:
    - ➡ radial flow
    - ➡ coalescence/recombination
    - ➡ jet fragmentation…



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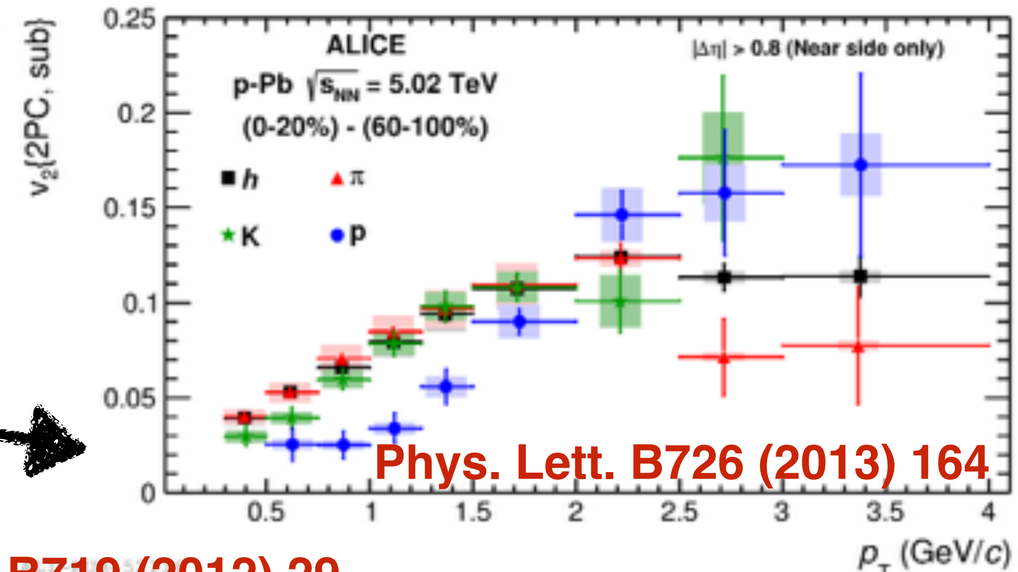

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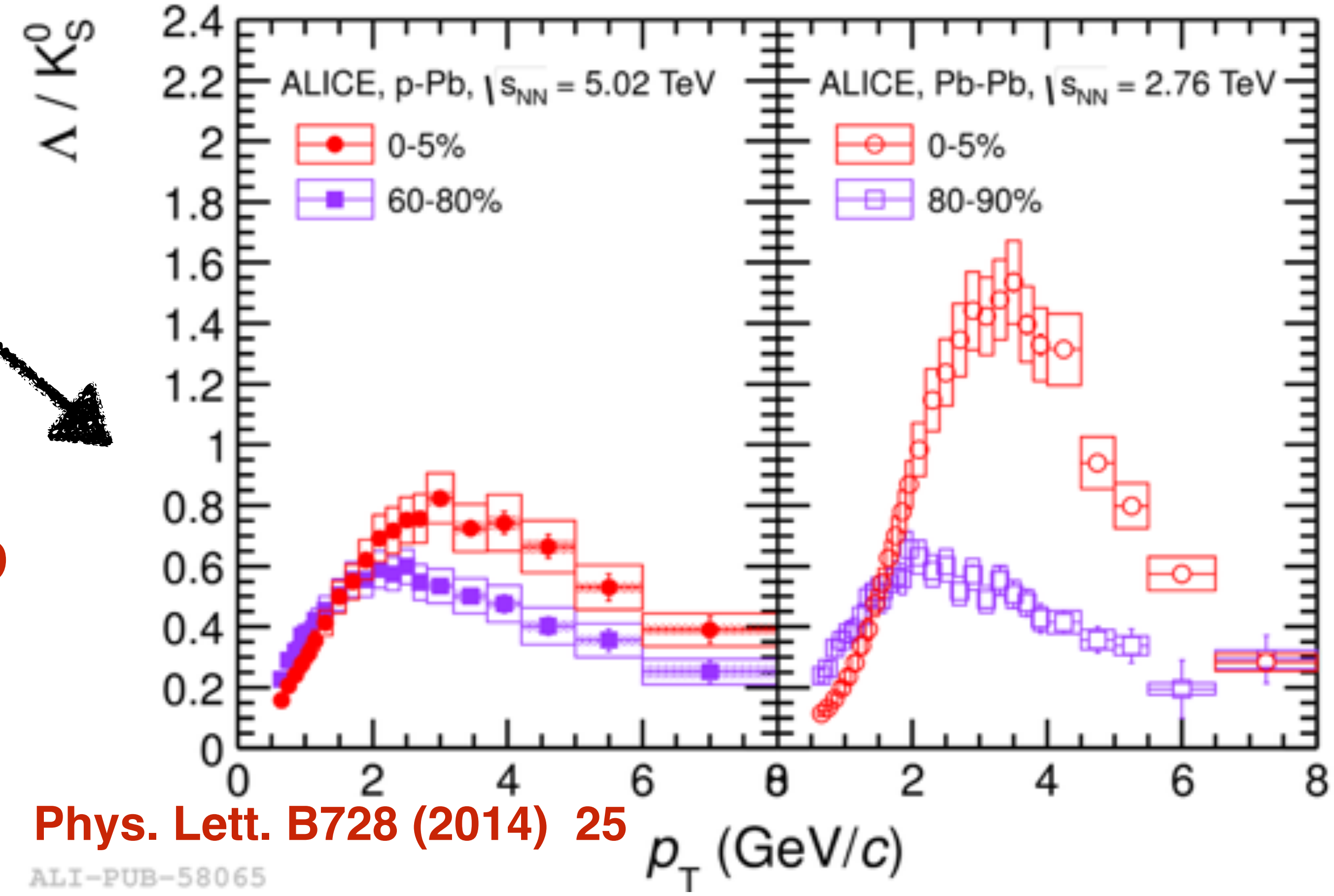

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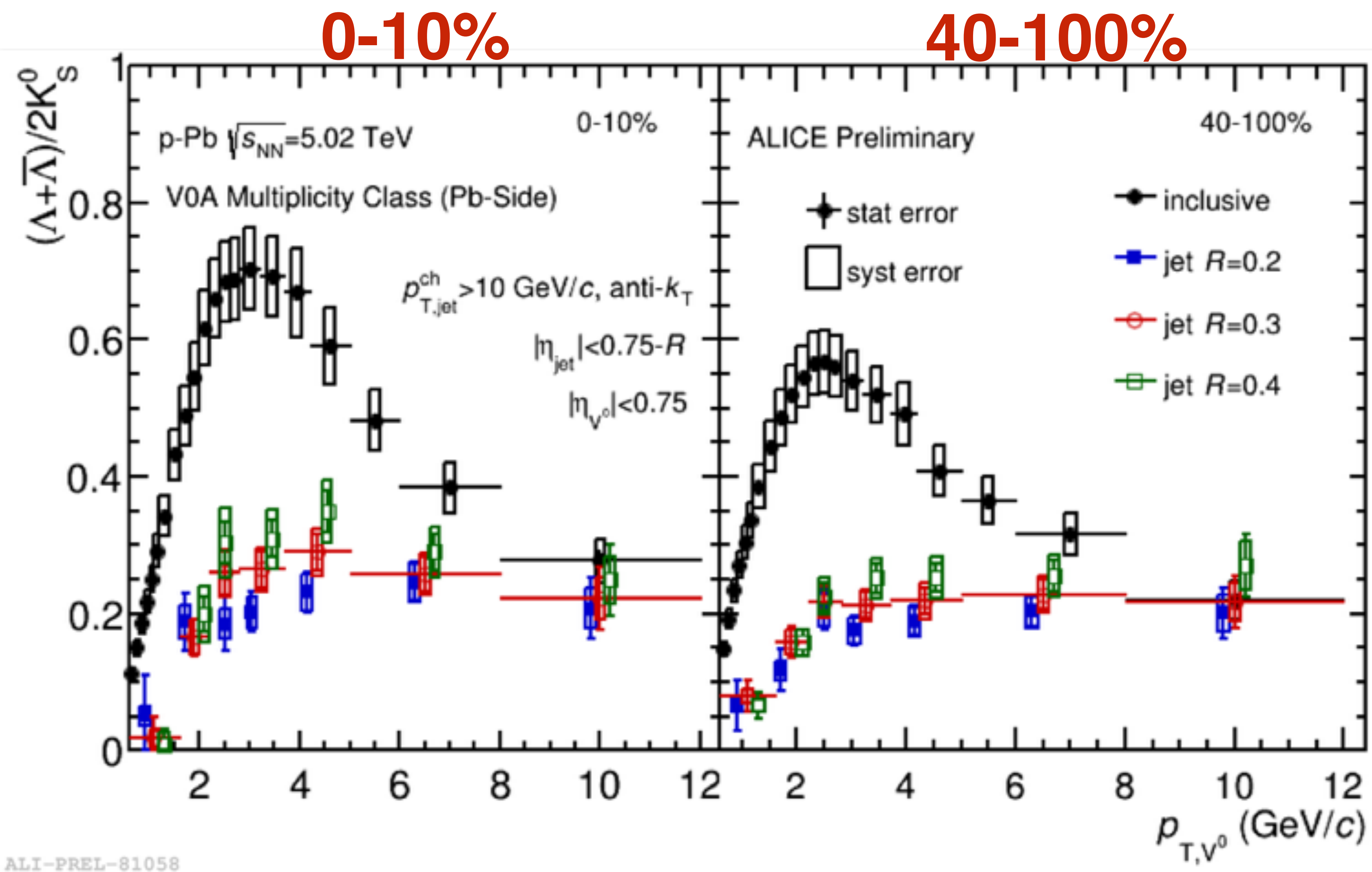
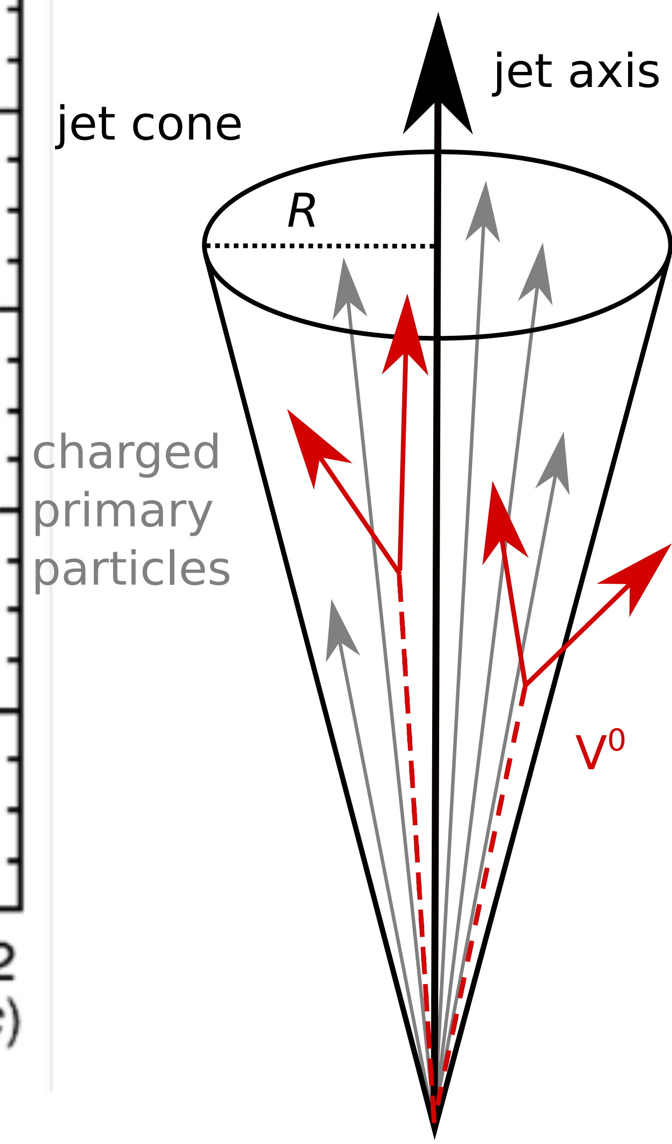
This analysis: Λ/K_S^0 ratio in jets in p–Pb

➡ separation of soft and hard processes

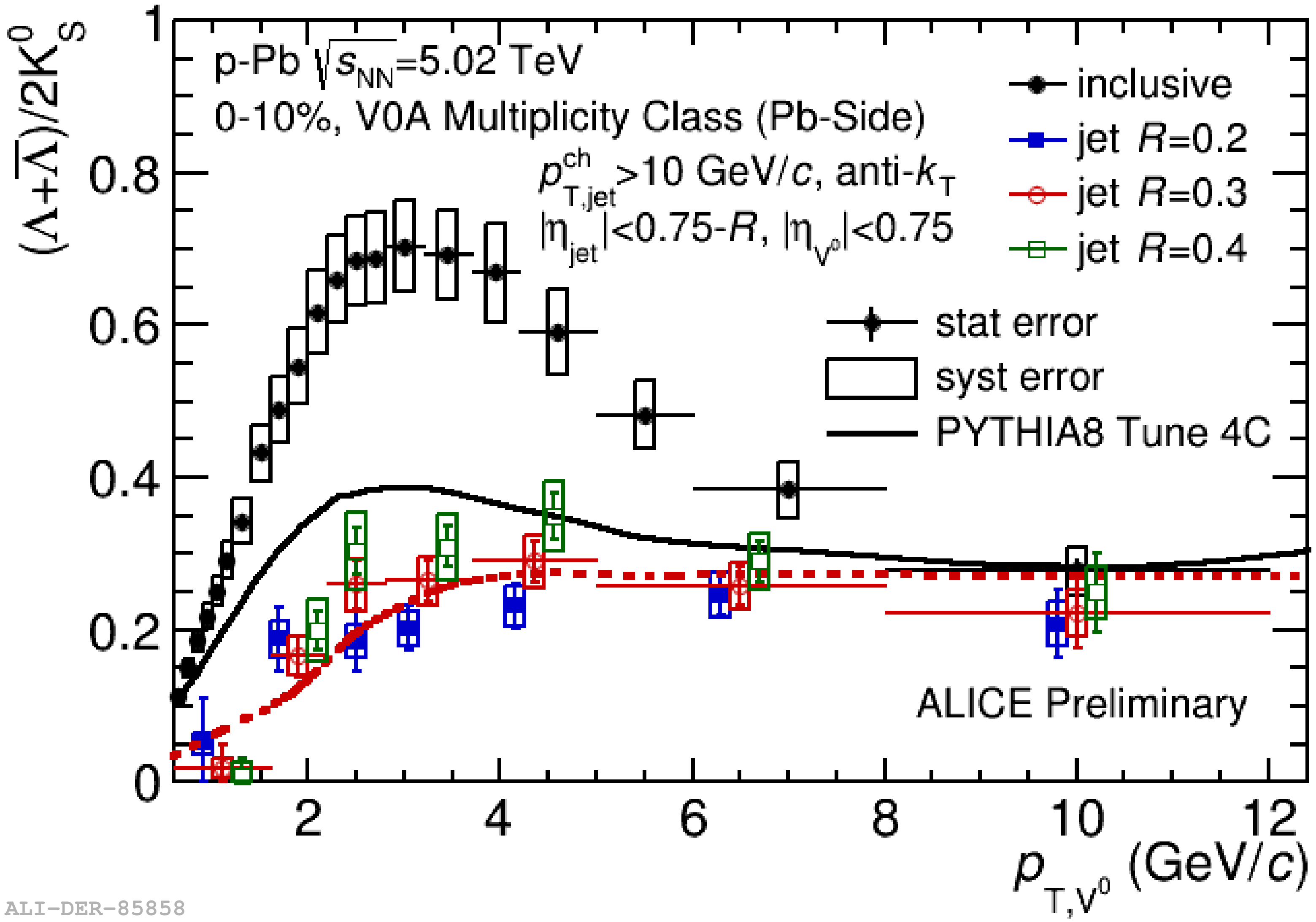
Λ/K_S^0 Ratio in Jets





- Λ/K_S^0 ratio significantly lower in jets than inclusive
- Ratio for different radii is the same within uncertainties
- Similar observation within errors for high and low multiplicity events

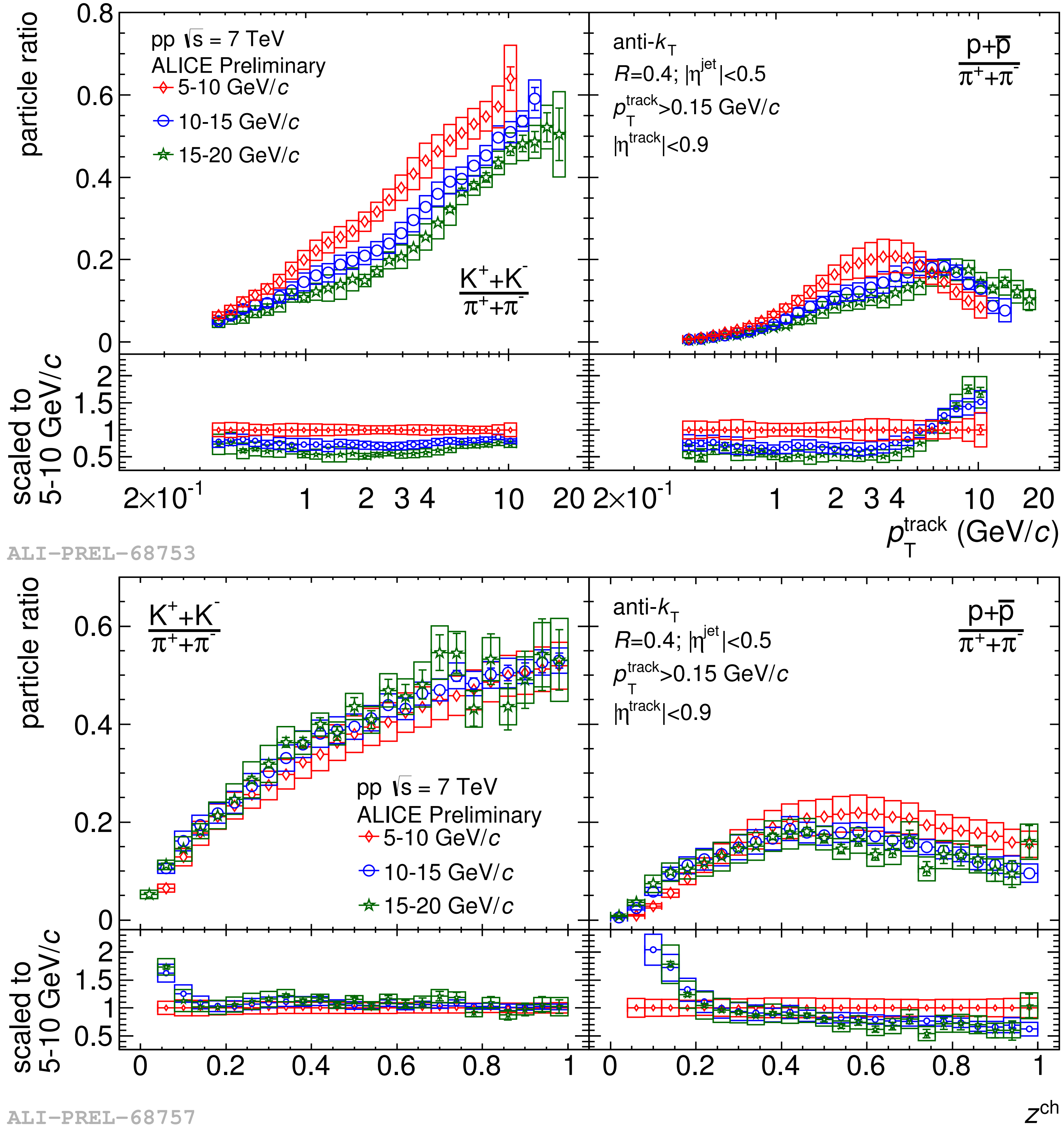
Comparison with PYTHIA



- Λ/K_S^0 ratio consistent with PYTHIA simulations
  - underlying event dominated by soft particle production
  - ➡ an interplay of radial flow and jets with little room for coalescence/recombination mechanism (?)
  - ➡ Next step: Proton/ϕ ration in jets — mass dependence

K/π and P/π ratios in Jets in pp Collisions

- K/π ratio increases with z/p_T
- Proton/π ratio suppression at high z/p_T
- No scaling with particle p_T observed
- scaling in $z > 0.2$

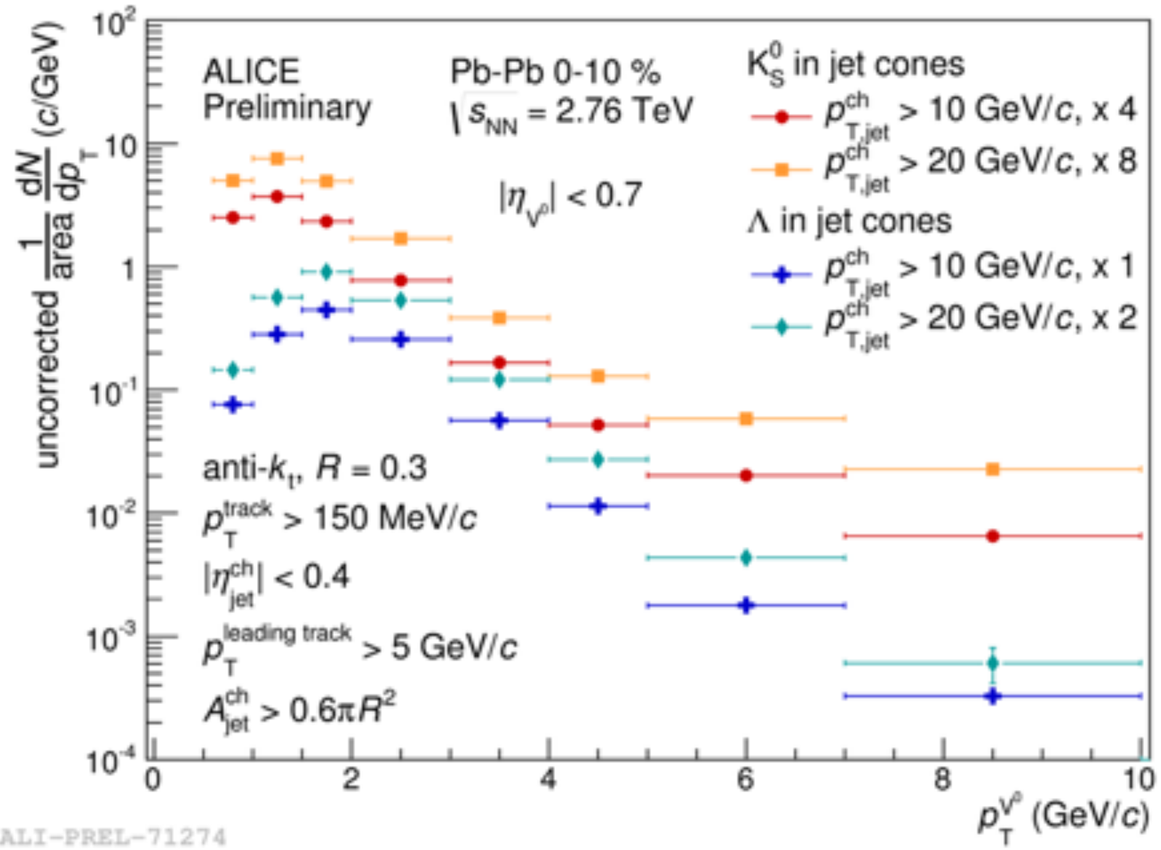


Conclusion

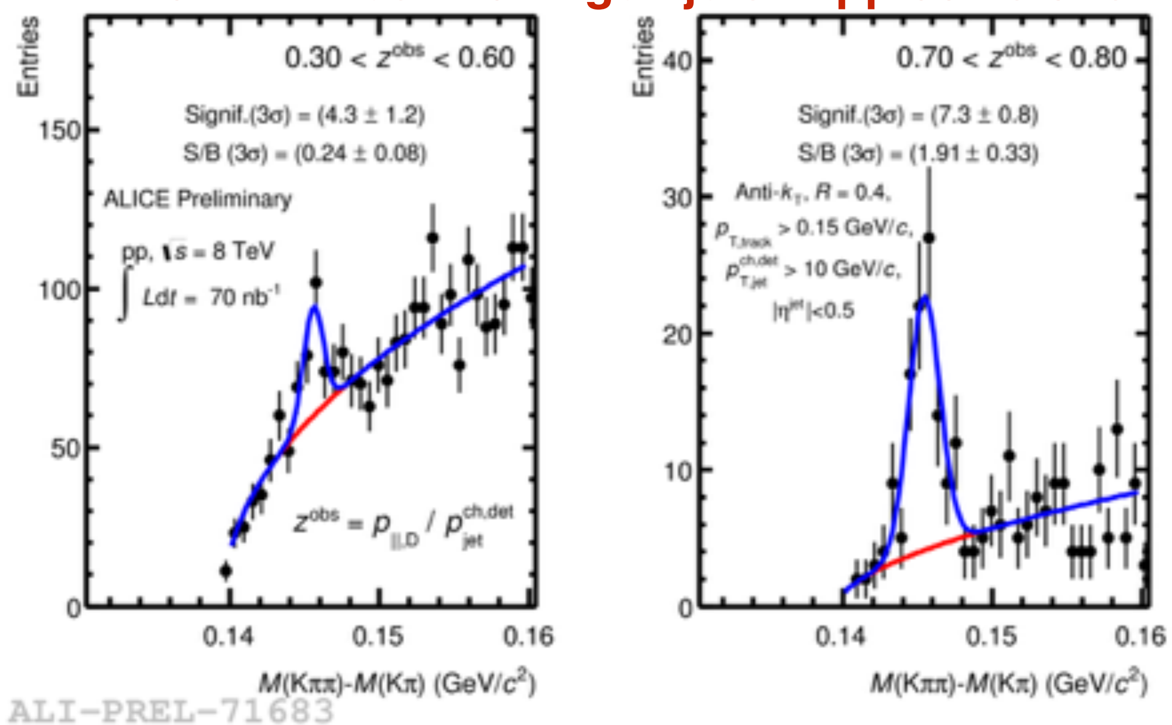
- **Pb—Pb collisions**
  - large jet yield suppression — $R_{AA}, R_{CP} < 1$
  - no significant energy redistribution within $R < 0.4$
    ➡ ratio of jet and Δ_{recoil} spectra consistent with vacuum jets
  - no evident medium-induced acoplanarity
    ➡ $\Delta_{recoil}(\Delta\phi)$ distribution reproduced by PYTHIA
  - non-vanished jet v_2 in semi-central collisions

- **p–Pb collisions**
  - no indication of cold nuclear effects for jet observables
    ➡ jet $R_{pPb} = 1$, dijet k_T in agreement with vacuum case
  - underlying event dominated by soft particle production
    ➡ the enhanced ratio of Λ/K_S^0 is not present within the jet region

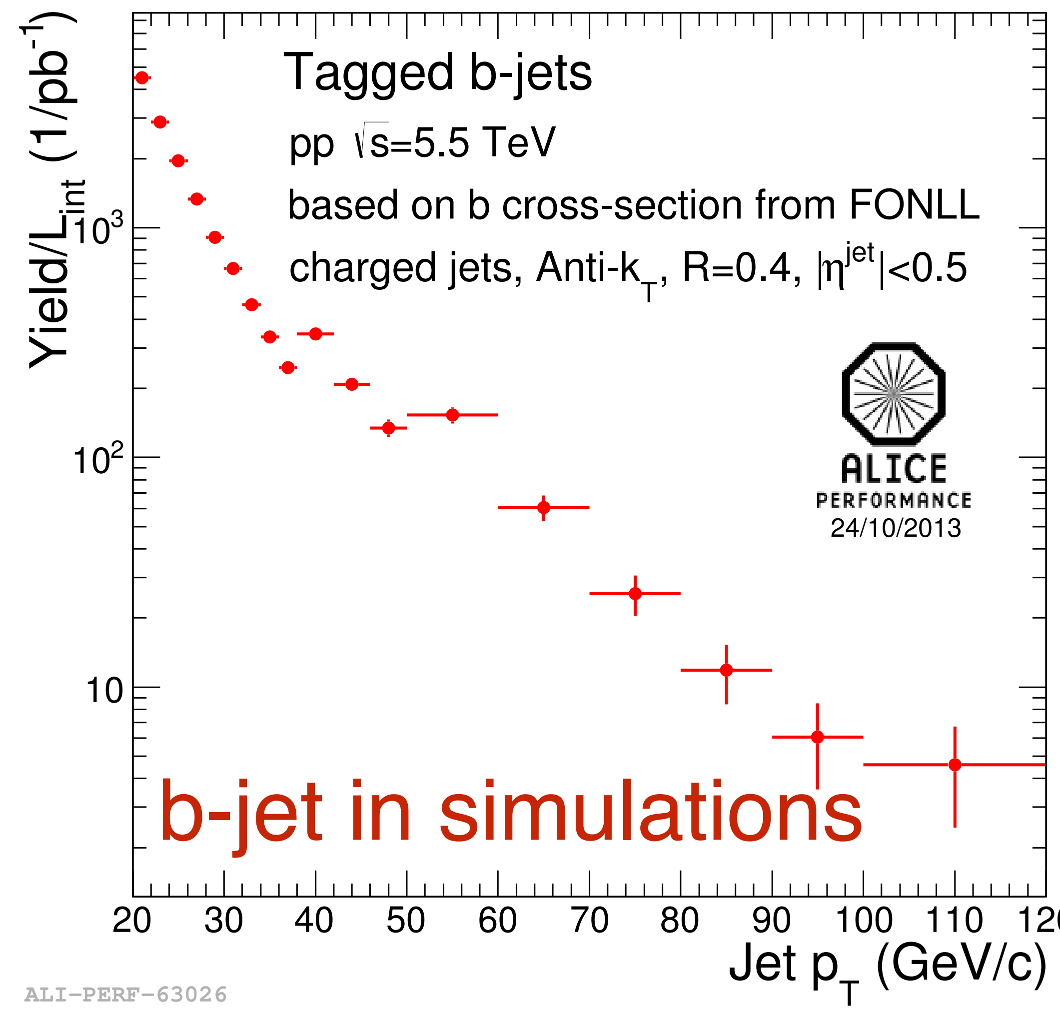
Outlook: PID in Jets



D* candidates in charged jets in pp collisions



More results will come from ALICE in the upcoming LHC run-II and run-III data!



Backup

Background Scale Factor